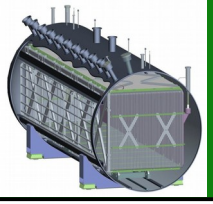
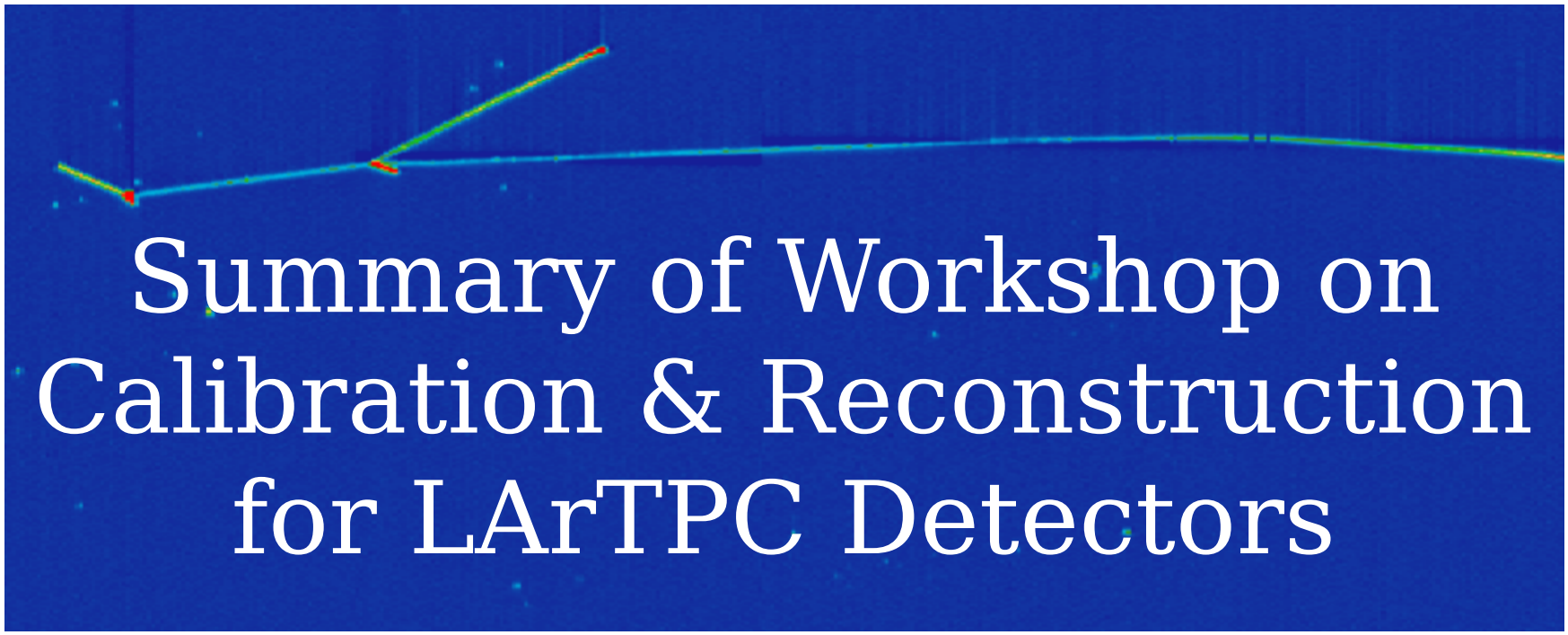




Summary of Workshop on Calibration & Reconstruction for LArTPC Detectors

Michael Mooney

Colorado State University

Fermilab Neutrino Seminar Series

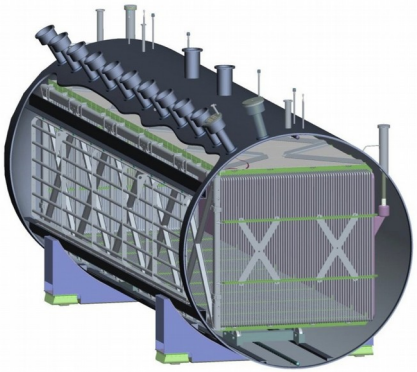
January 24th, 2019

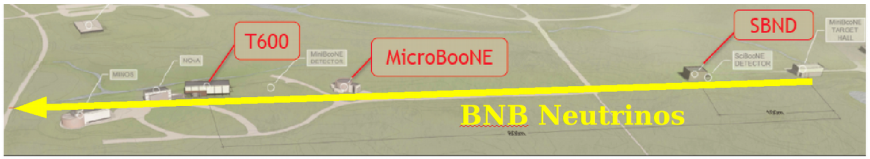
Introduction

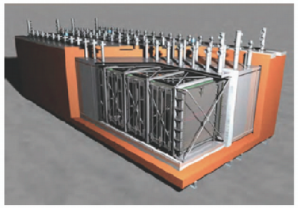
- Workshop held on Dec. 10th and 11th at Fermilab
  - NPC funded
  - 60+ participants
  - 30+ invited talks
- Purpose:
  - Compensate for personnel shortage in LArTPC neutrino community
  - Share tools and techniques
  - Identify needs of future experiments
  - Educate newcomers on intricacies of field

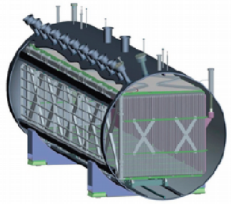
LArTPC ν Experiments

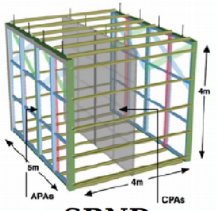
μBooNE






ICARUS-T600

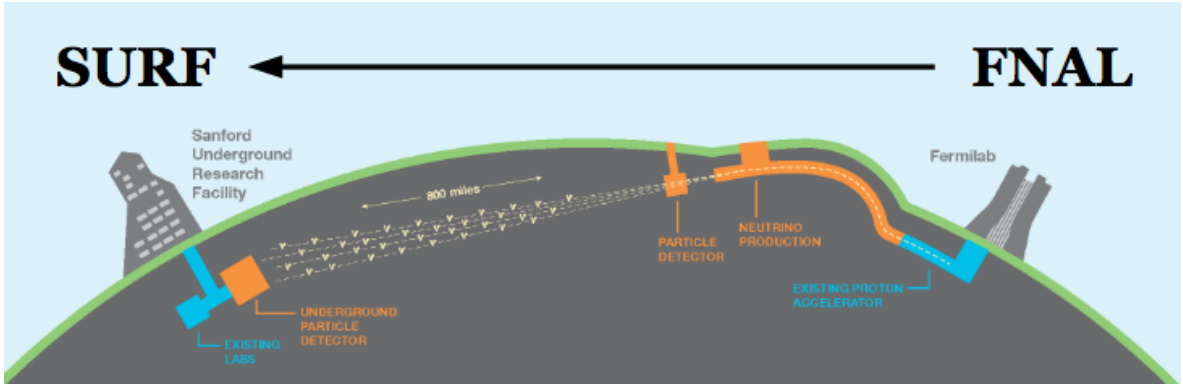

MicroBooNE

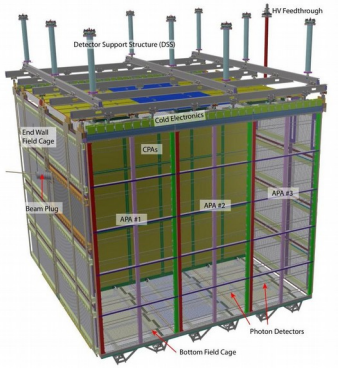


SBND

SBN

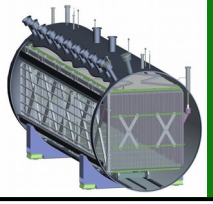
DUNE



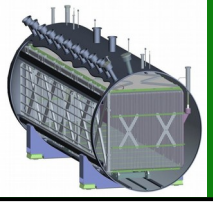


ProtoDUNE-SP

- Also heard from previous experiments at workshop:
  - **ArgoNeuT** (small, in ν beam), **LArIAT** (small, in charged beam), and previous running of **ICARUS** detector

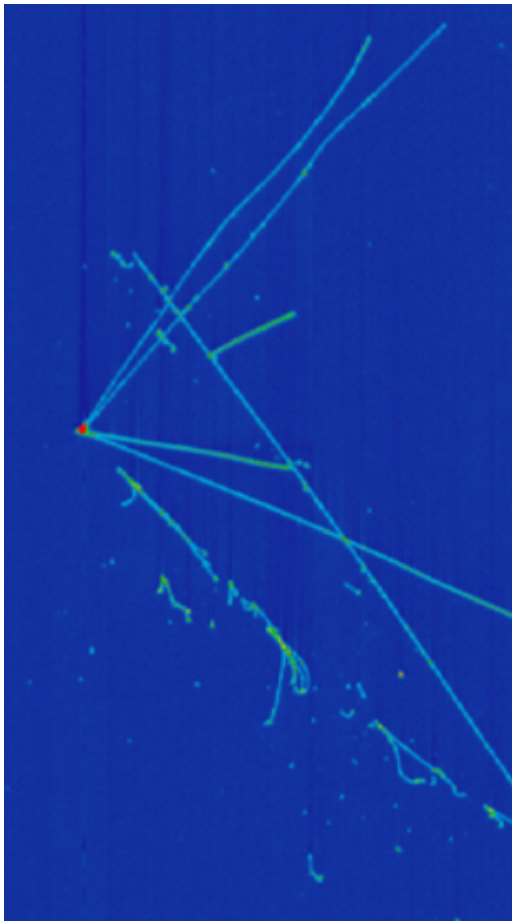


Overview of LArTPC Detectors



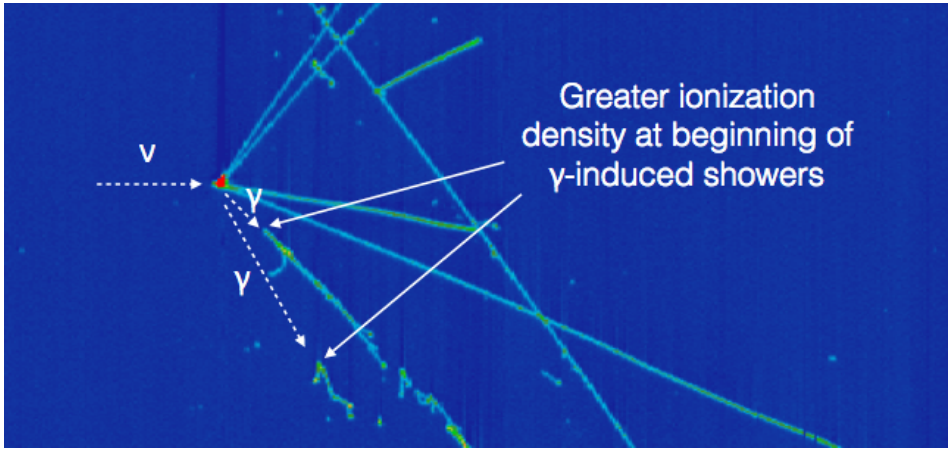
Introducing the LArTPC

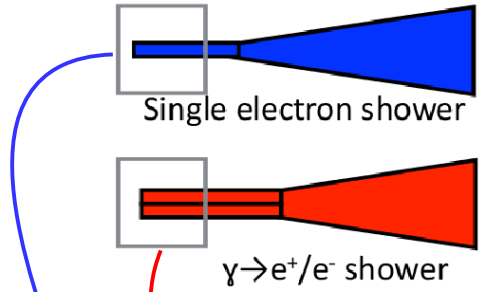
- Precision neutrino detector: the LArTPC
  - **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber
- Features of LArTPC detectors:
  - ***Low Thresholds*** – important for detecting low-energy particles (e.g. in SBN sterile neutrino search)
  - ***Excellent Calorimetry*** – important for precise estimation of neutrino energy, particle ID with dE/dx
  - ***High Spatial Resolution*** – allows for background rejection and particle ID
  - ***Scalability*** – large detectors yielding high event rates for precision physics (e.g. measurements at DUNE)

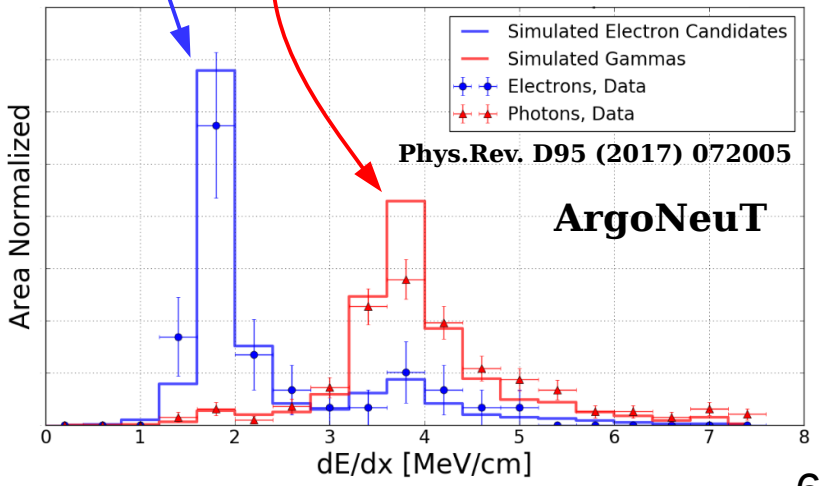


e/γ Discrimination

- Can discriminate e±/γ with LArTPC
  - Shower displacement from vertex ("gap") for γ also provides separation
  - Separation with dE/dx
- Important handles for reducing photonic backgrounds at μBooNE, SBN, and DUNE

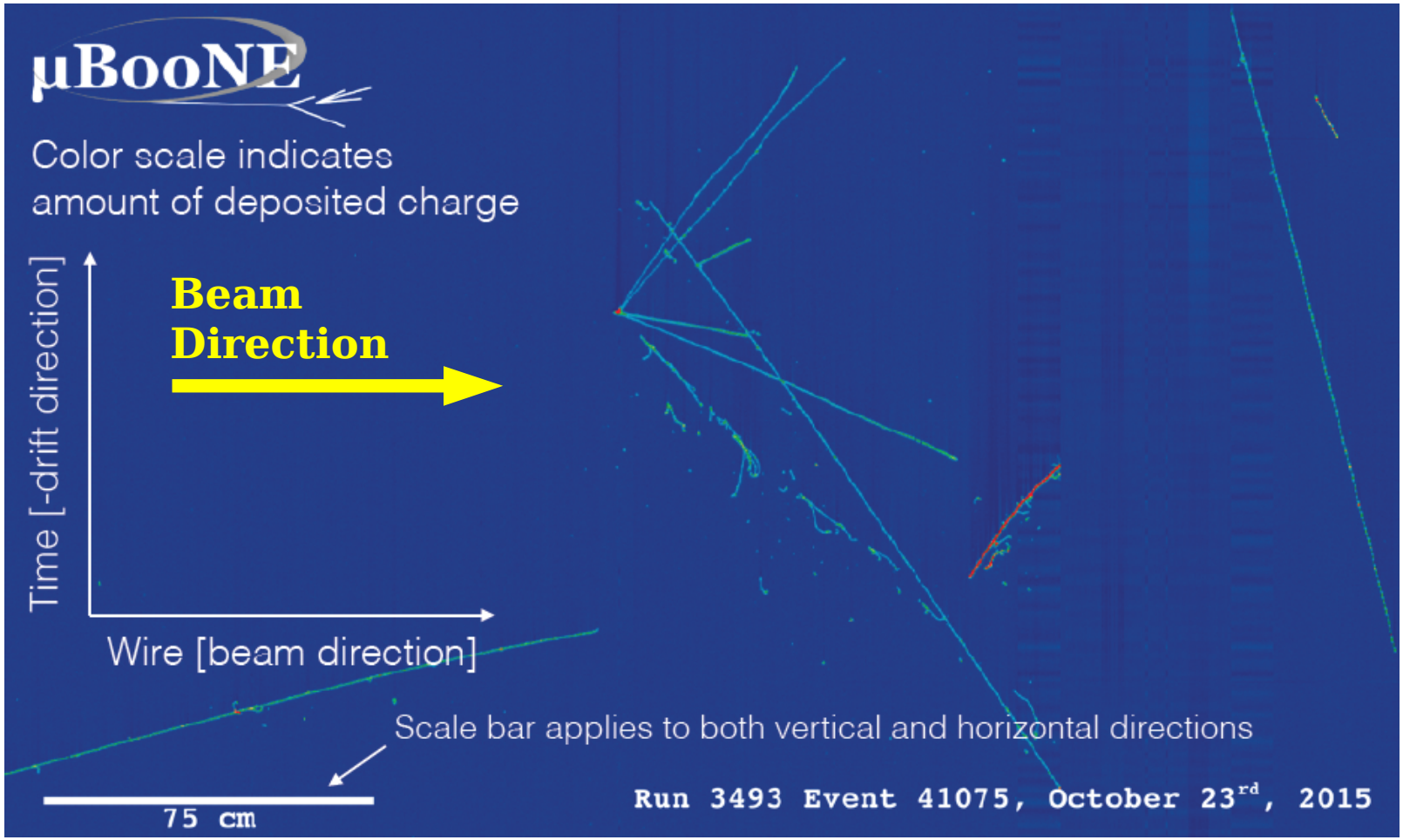


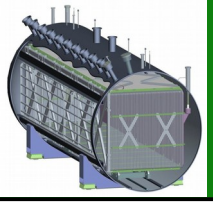




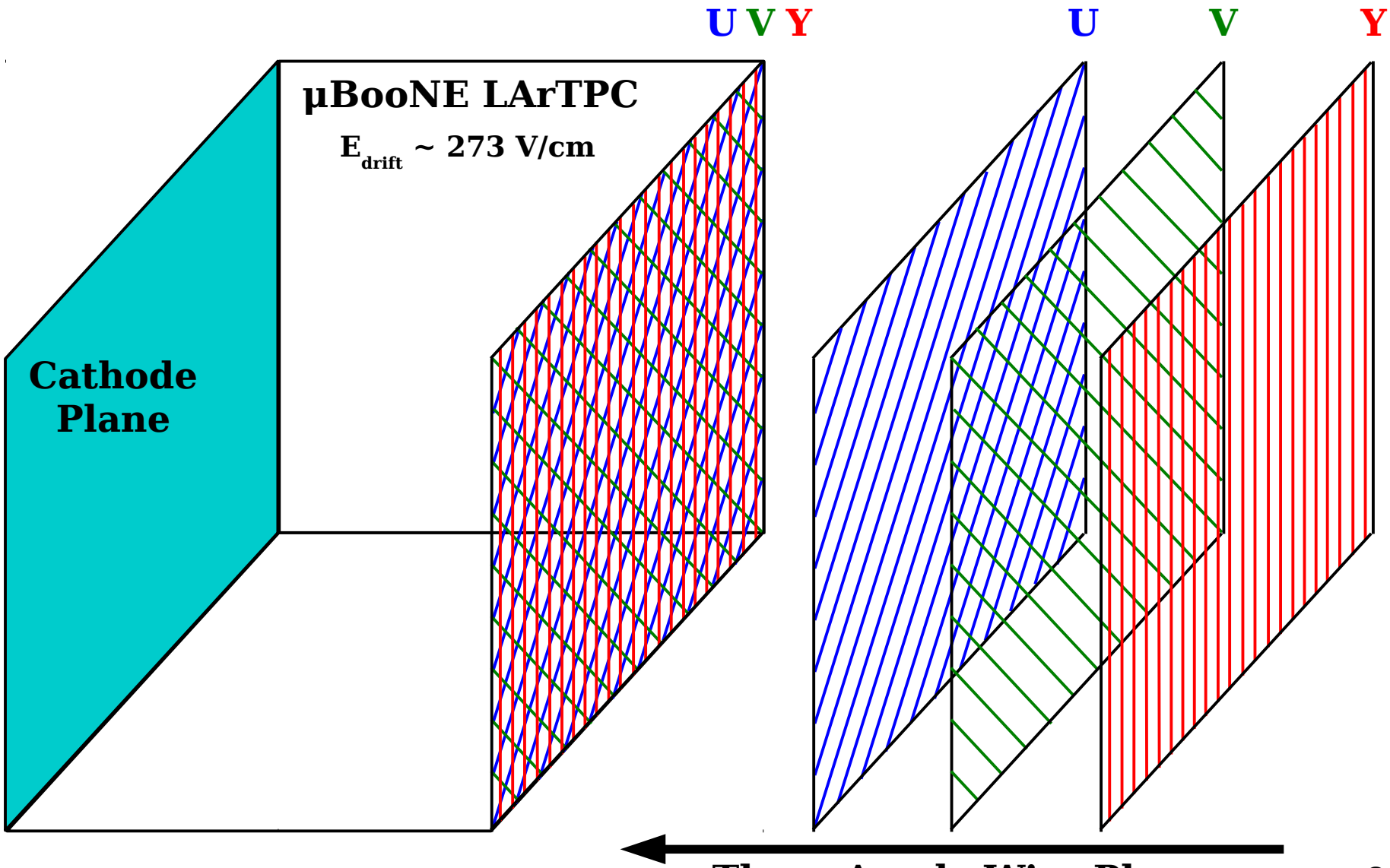
MicroBooNE Event Display

- Raw data representations are **images** with very fine-grained spatial resolution (~1 mm)!

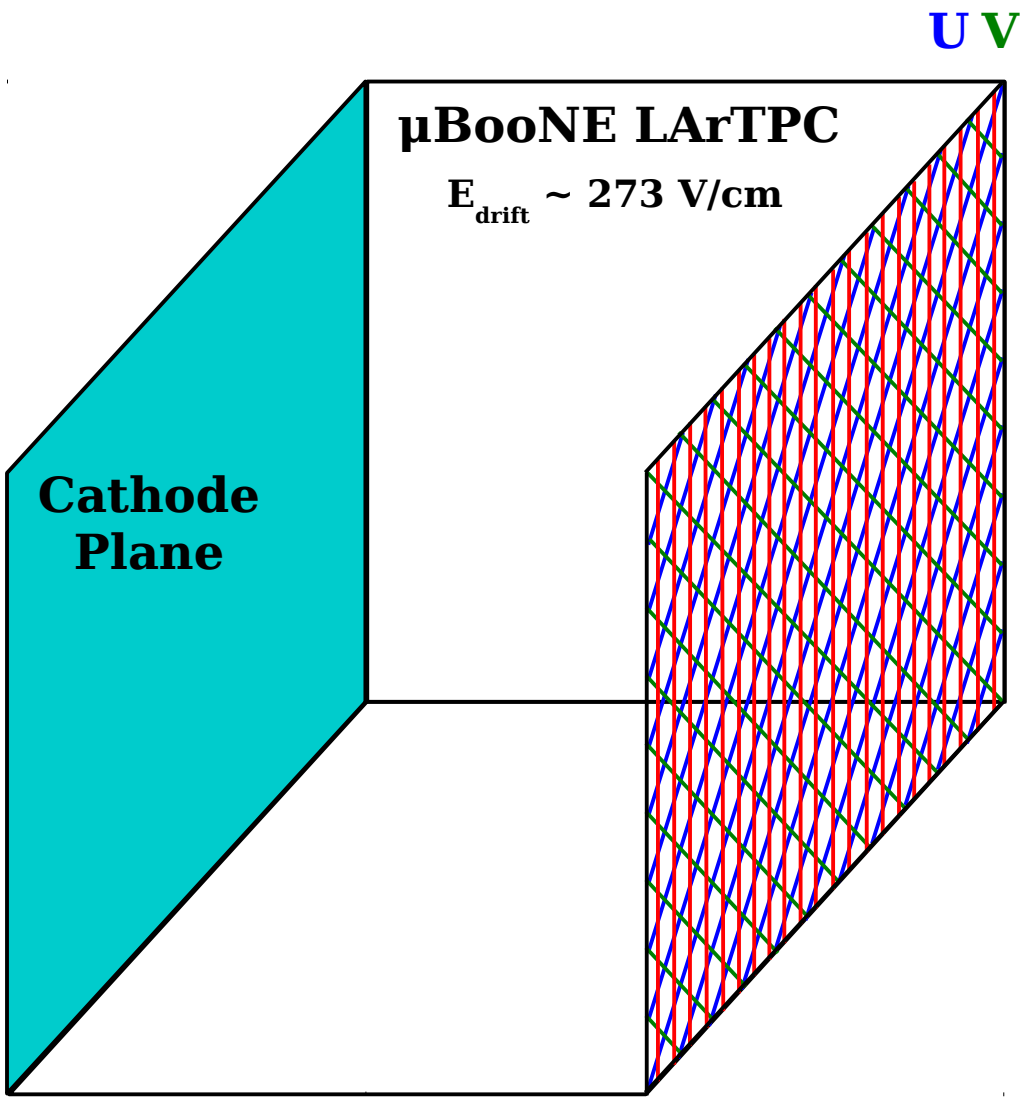


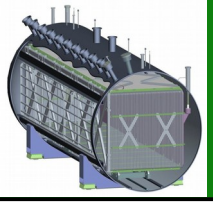


Signal Formation

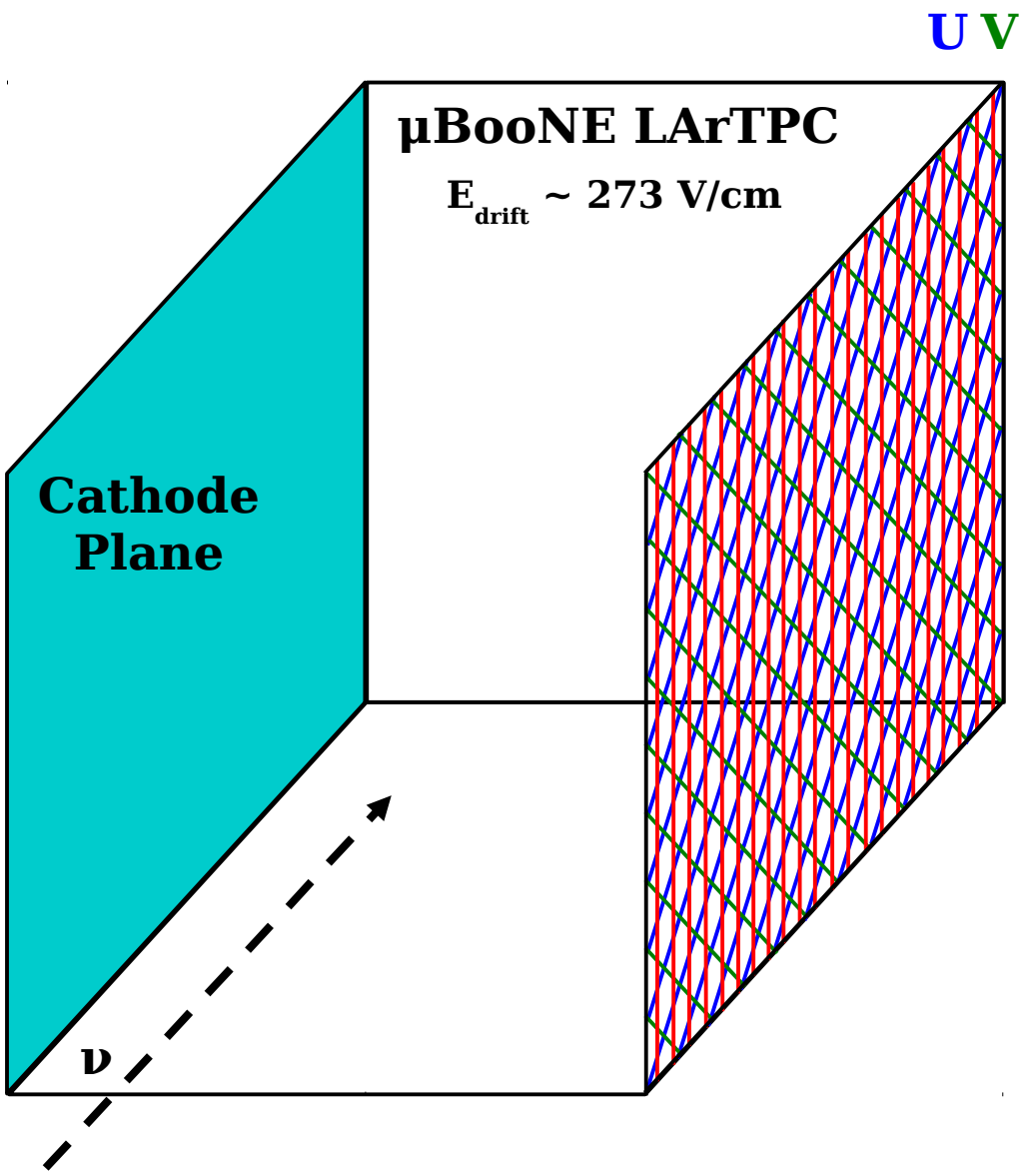


Signal Formation

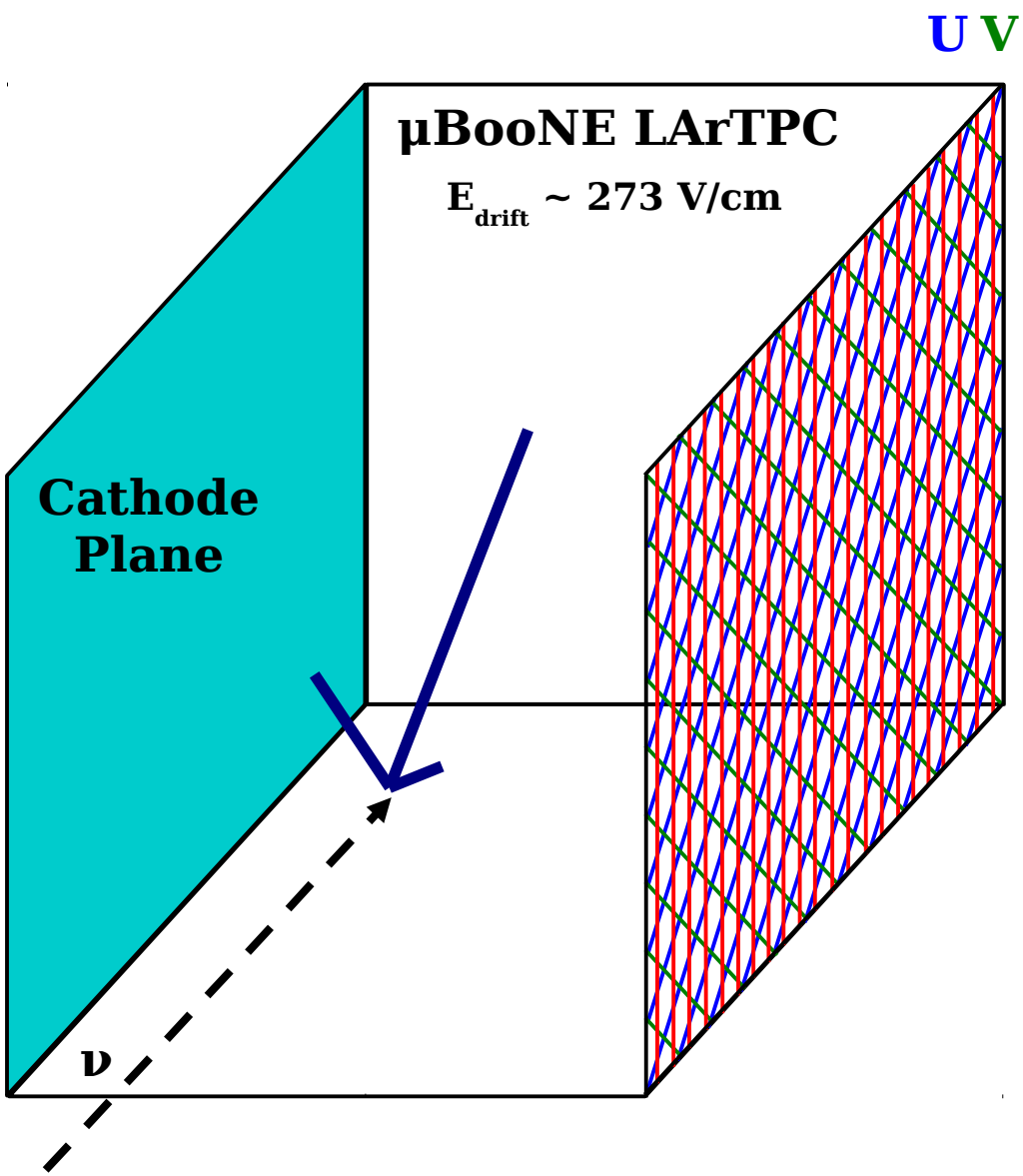




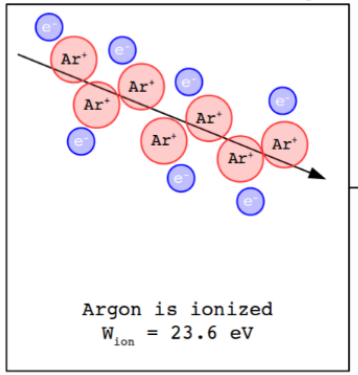
Signal Formation



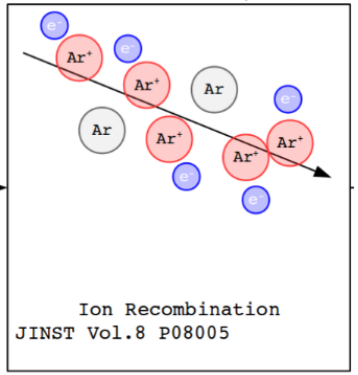
Signal Formation



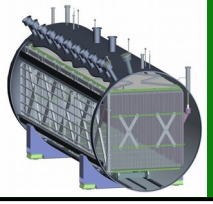
$$dQ = dE \times \frac{W_{ion}}{e^-}$$



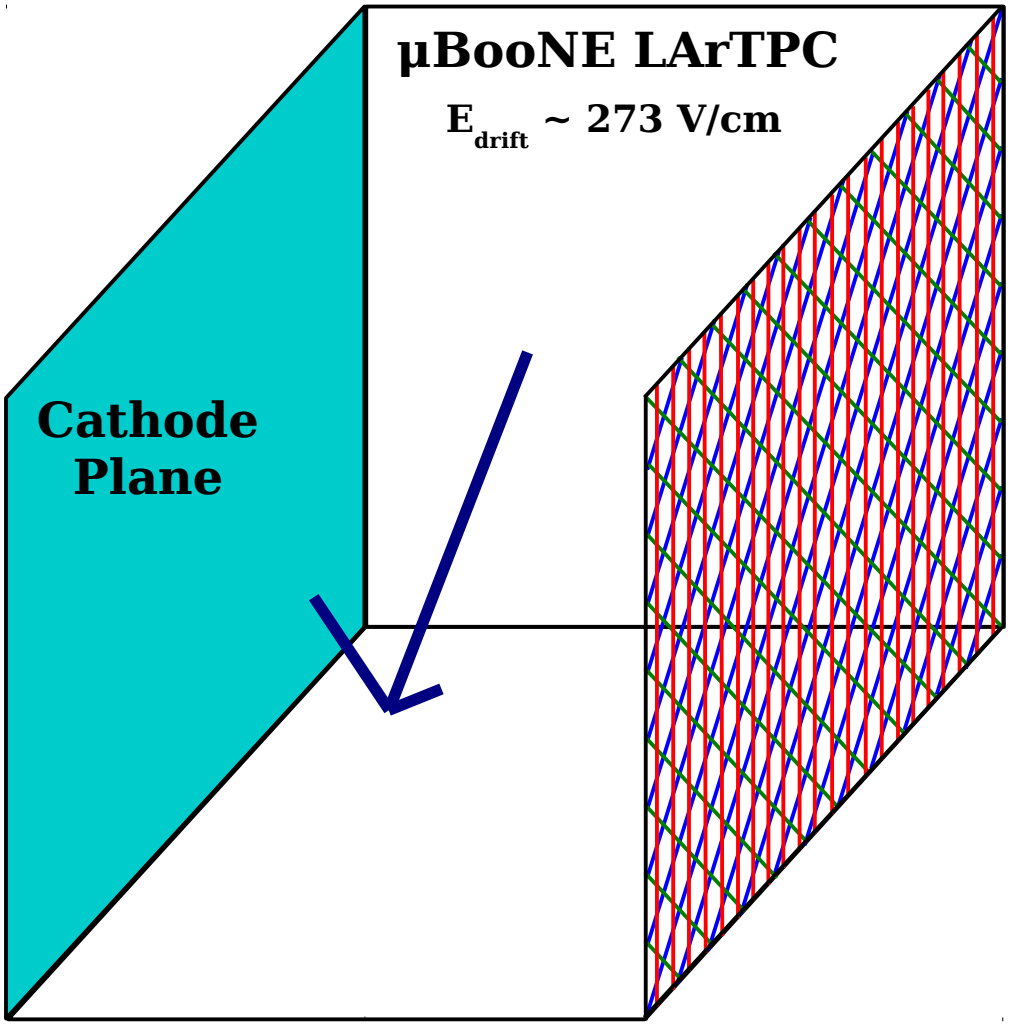
$$dE/dx = \frac{e^{\beta W_{ion} dQ/dx} - \alpha}{dE/dx\,\beta}$$



Signal Formation



U V Y



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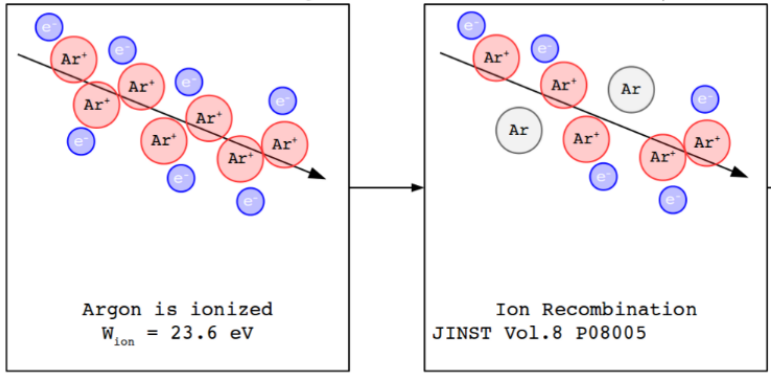
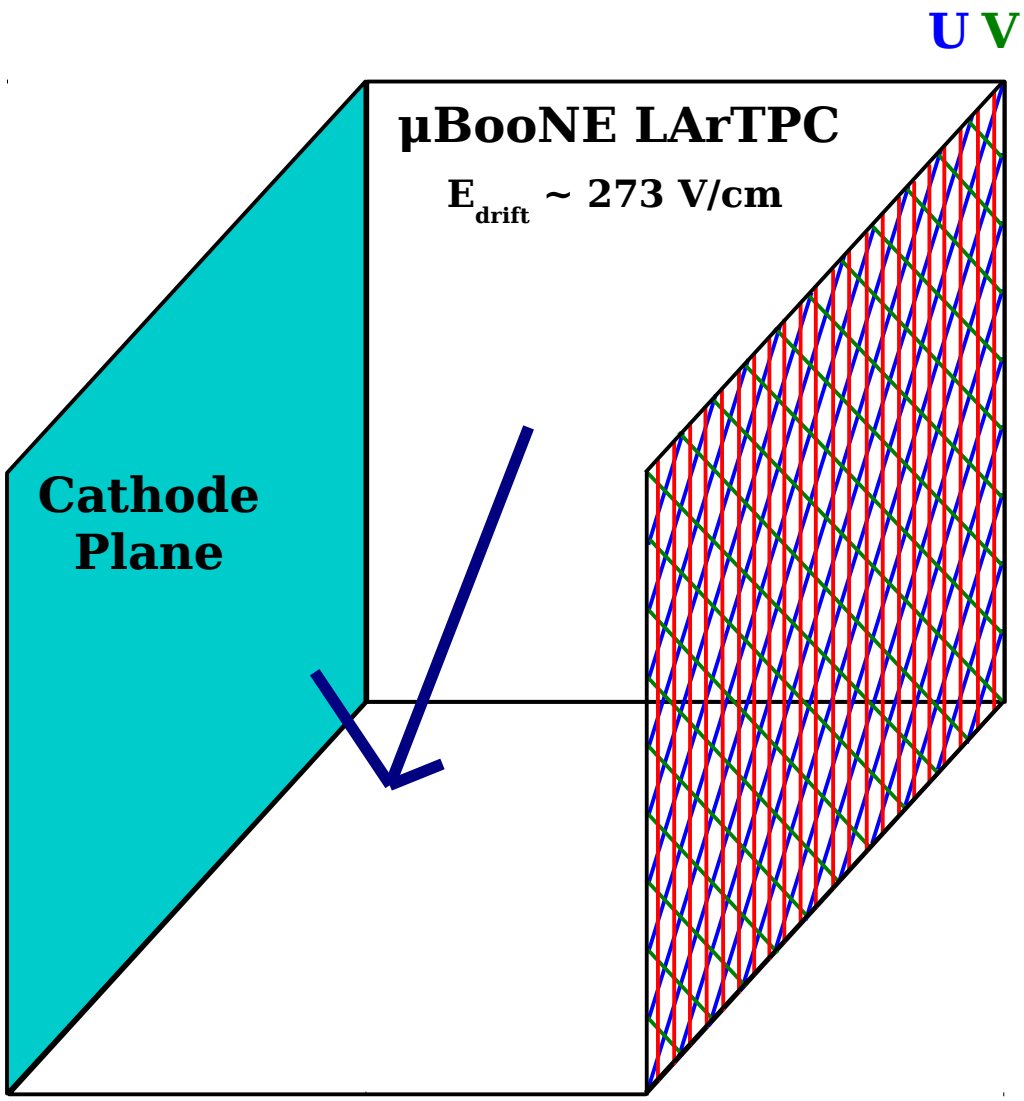
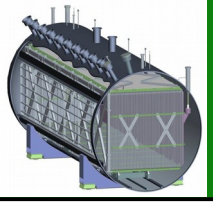
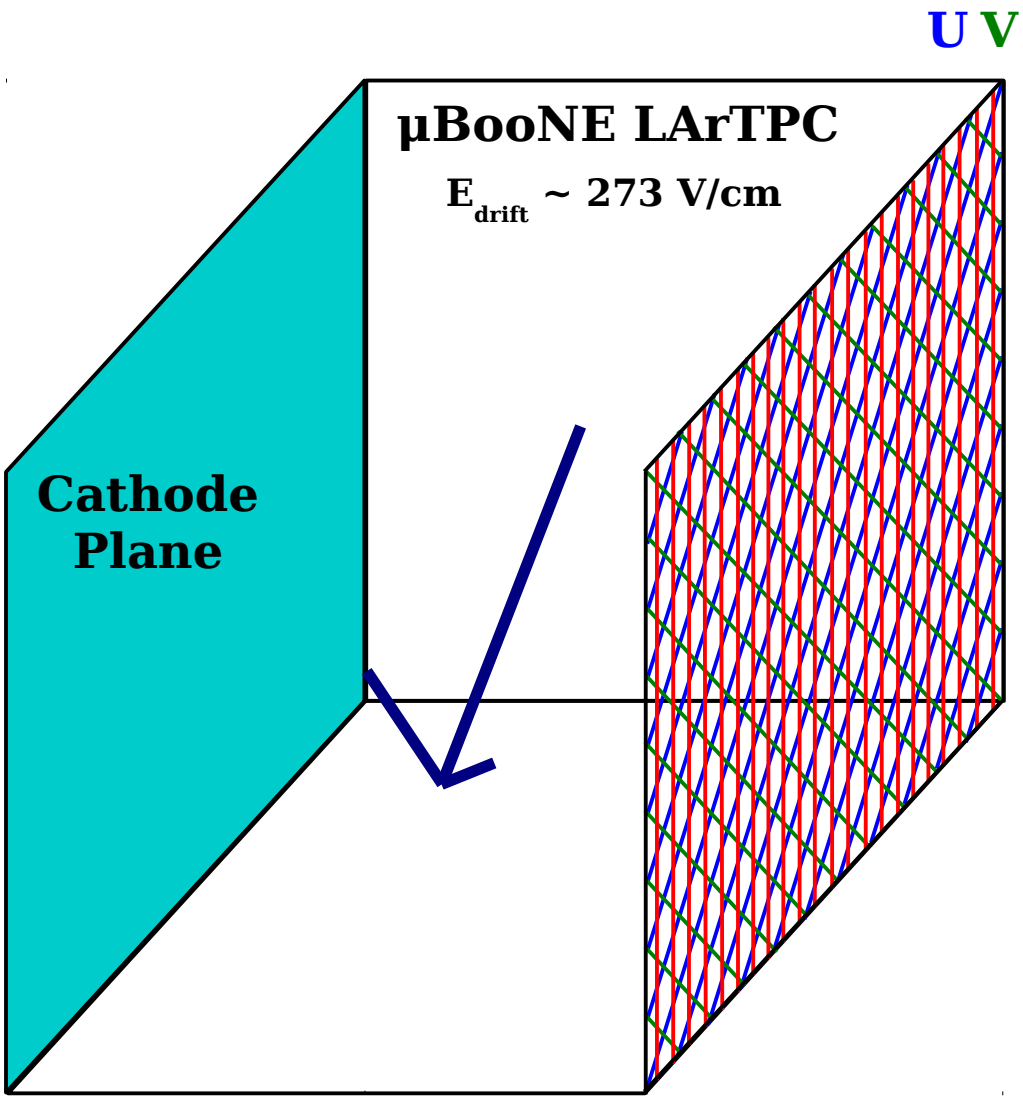


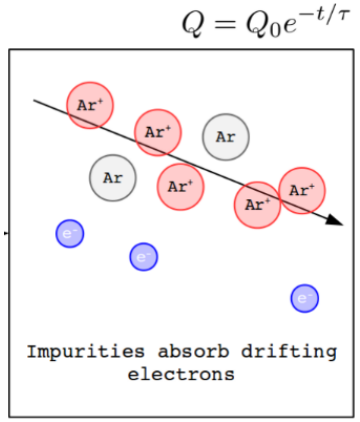
Signal Formation

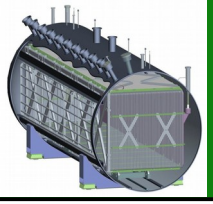




Signal Formation







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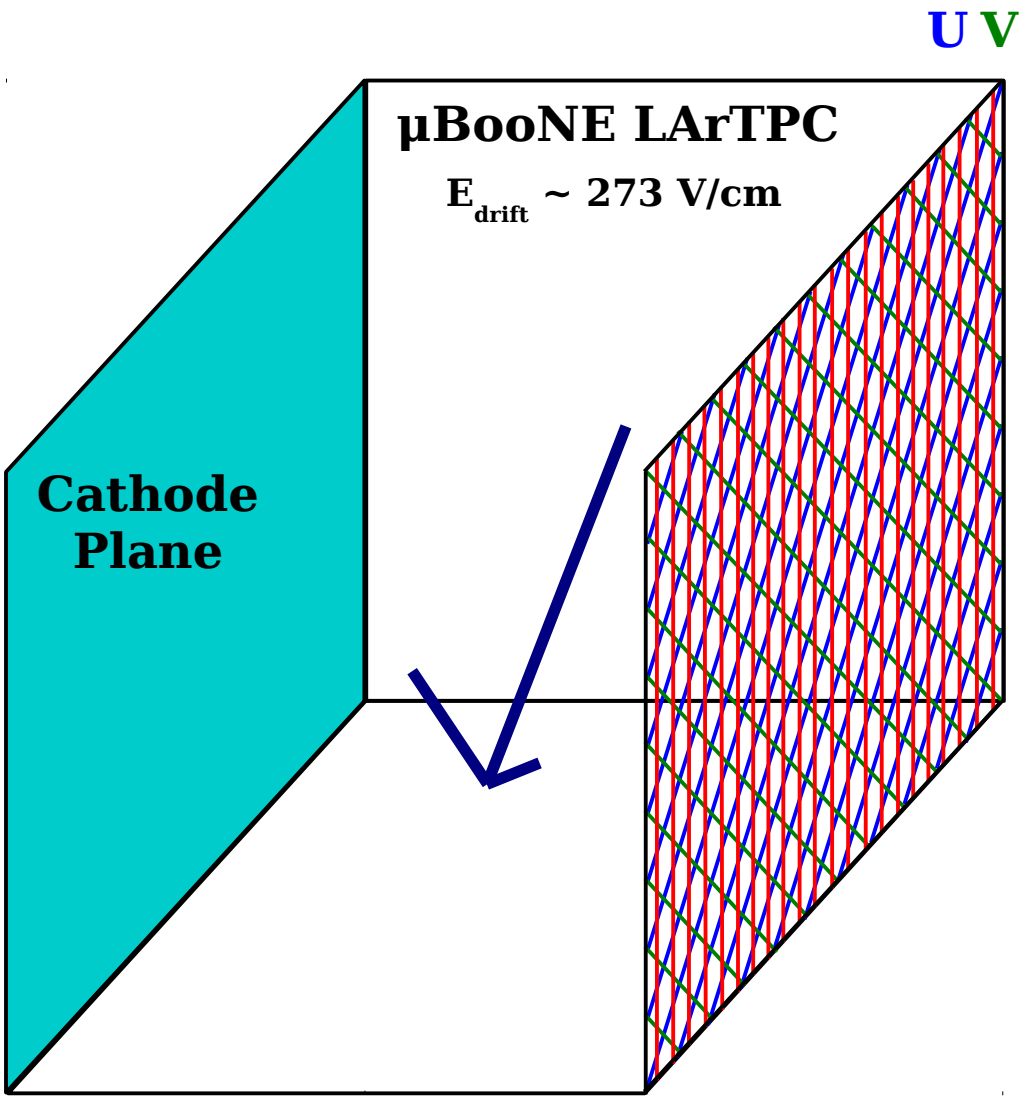
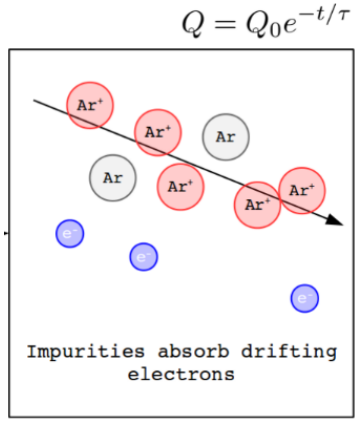
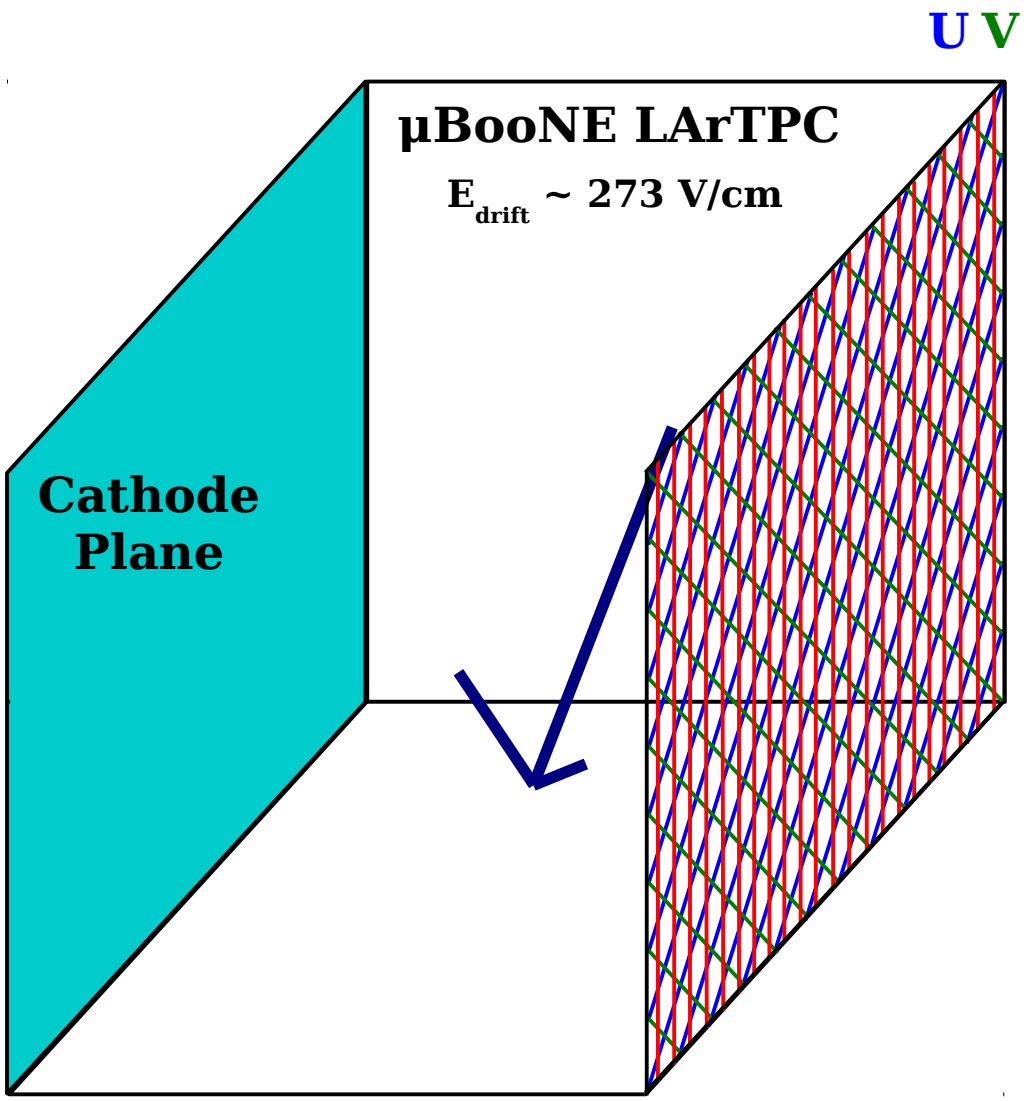
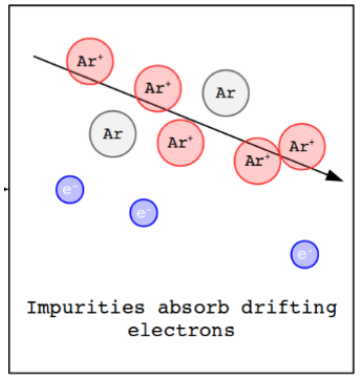


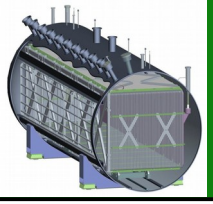


Signal Formation



$$Q = Q_0 e^{-t/\tau}$$





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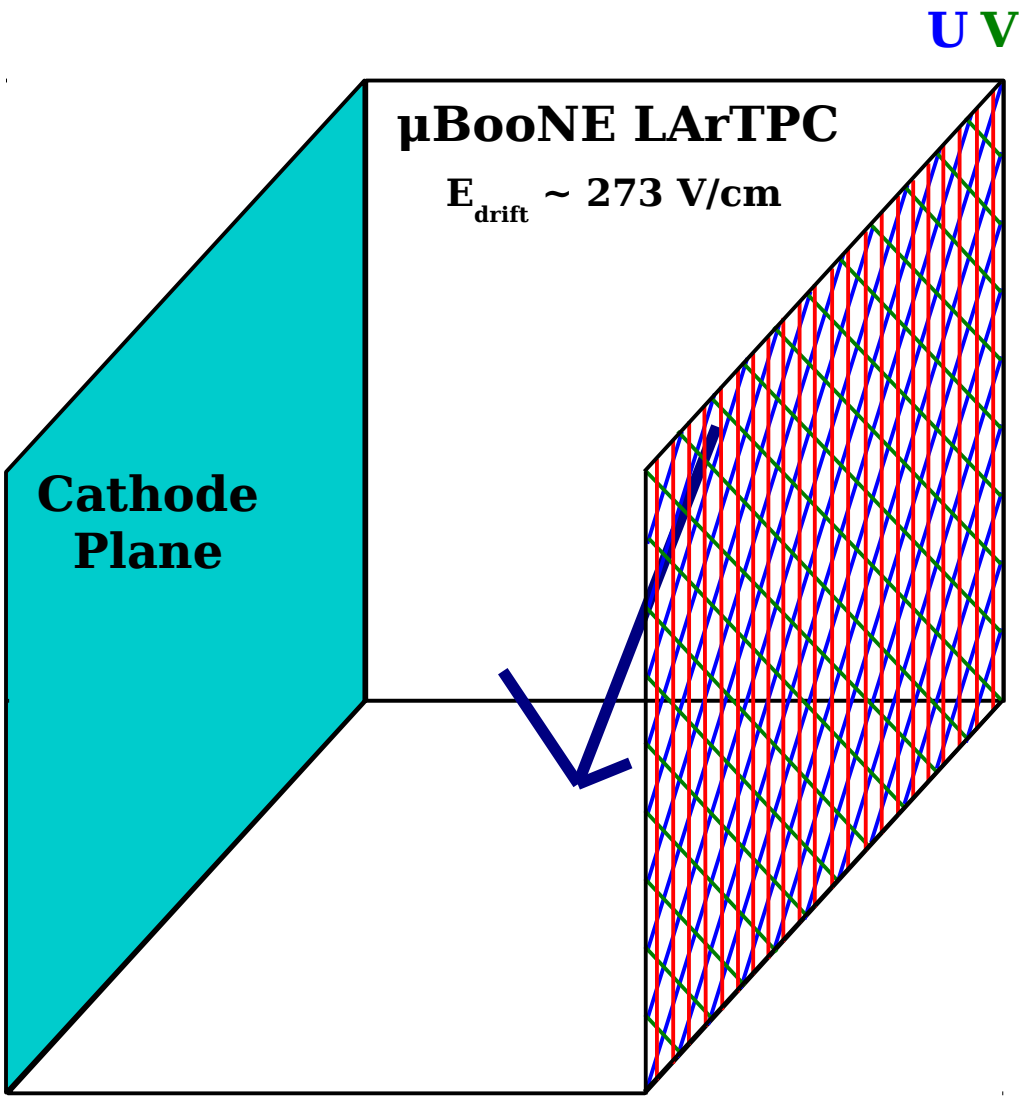

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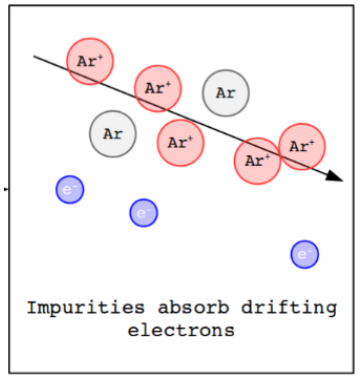

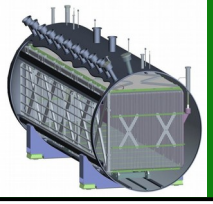

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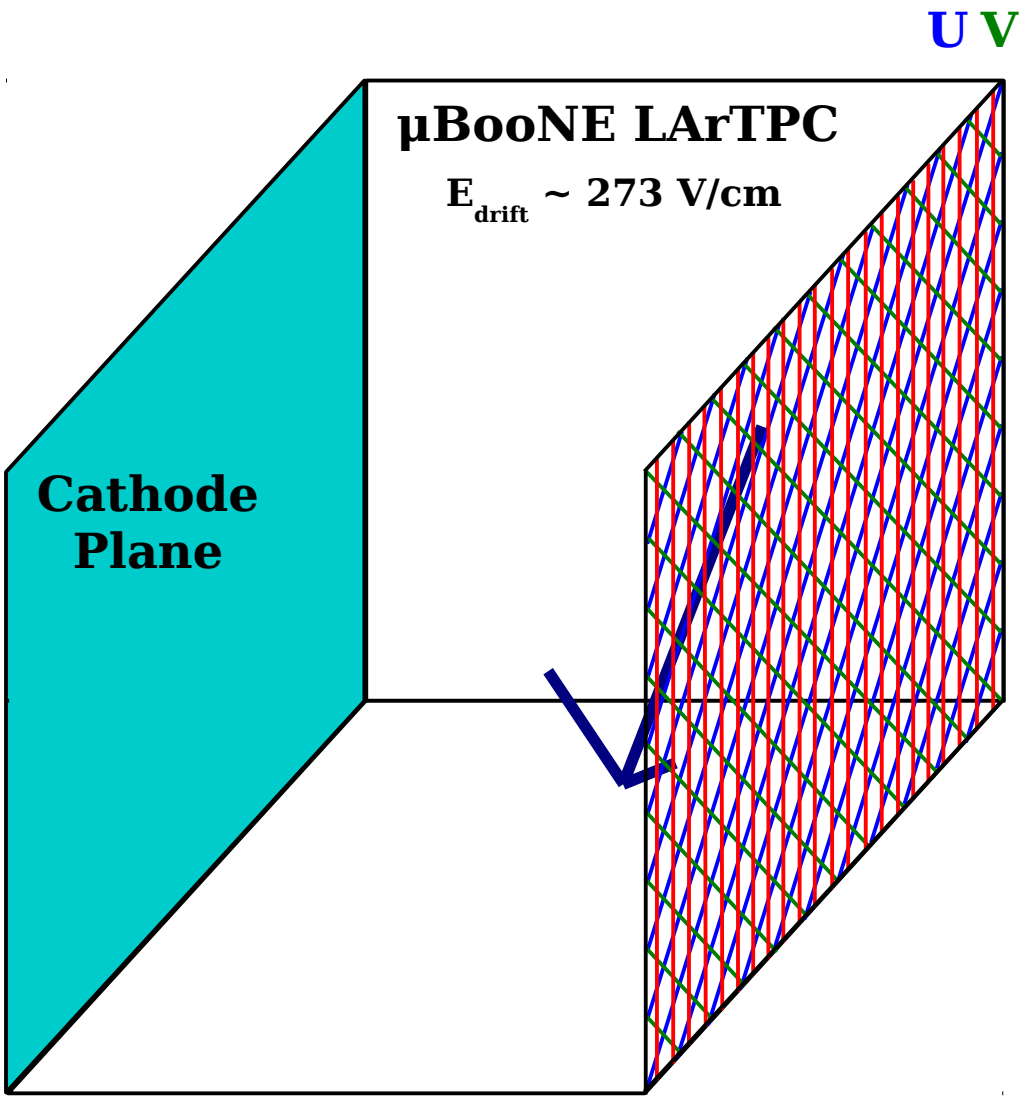

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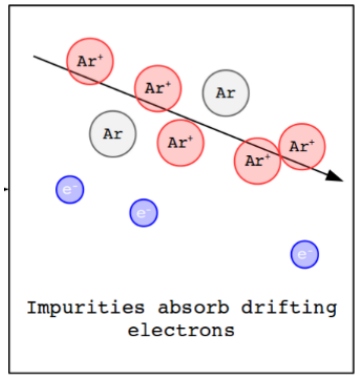
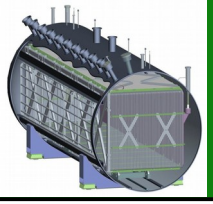
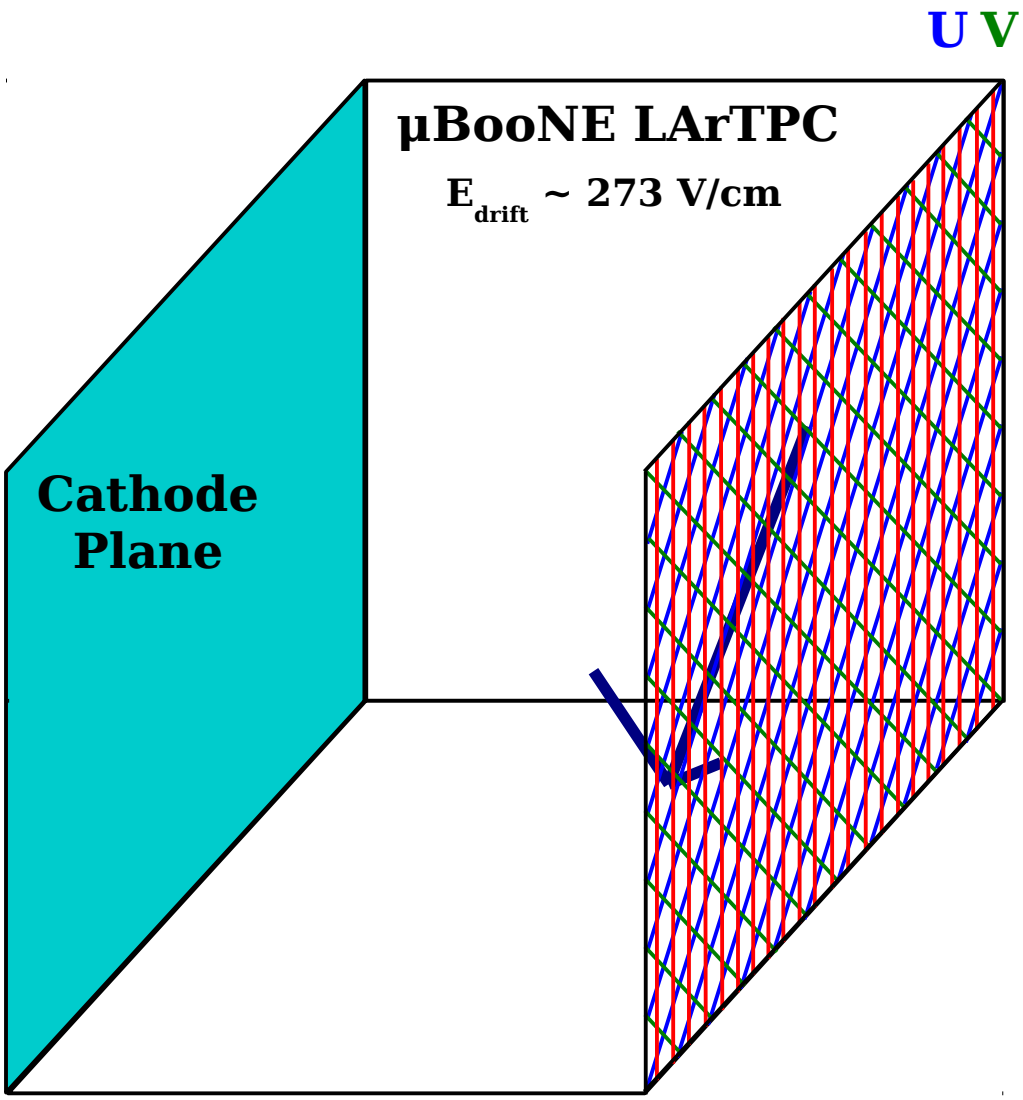




Signal Formation



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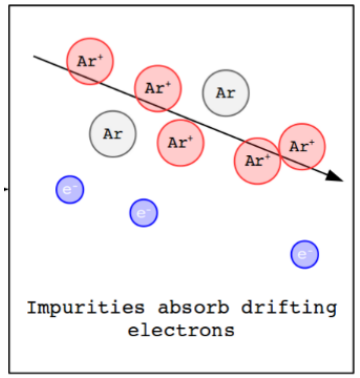

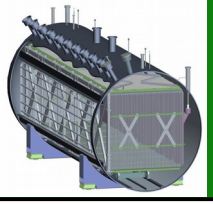

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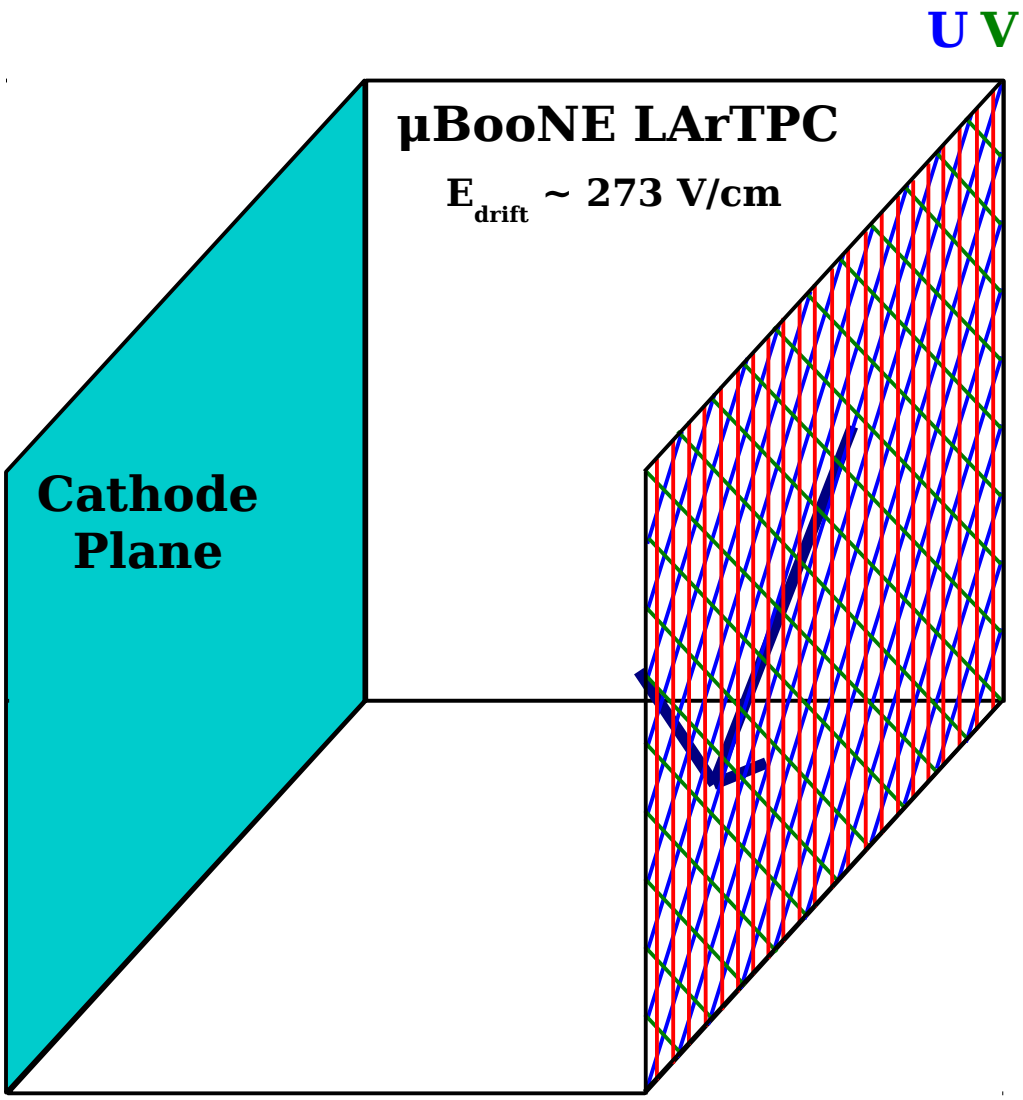

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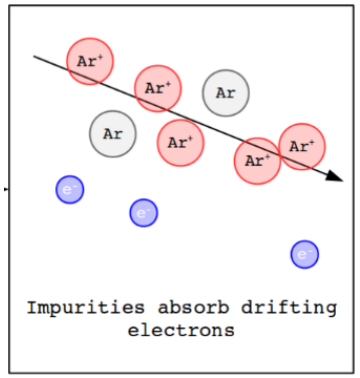

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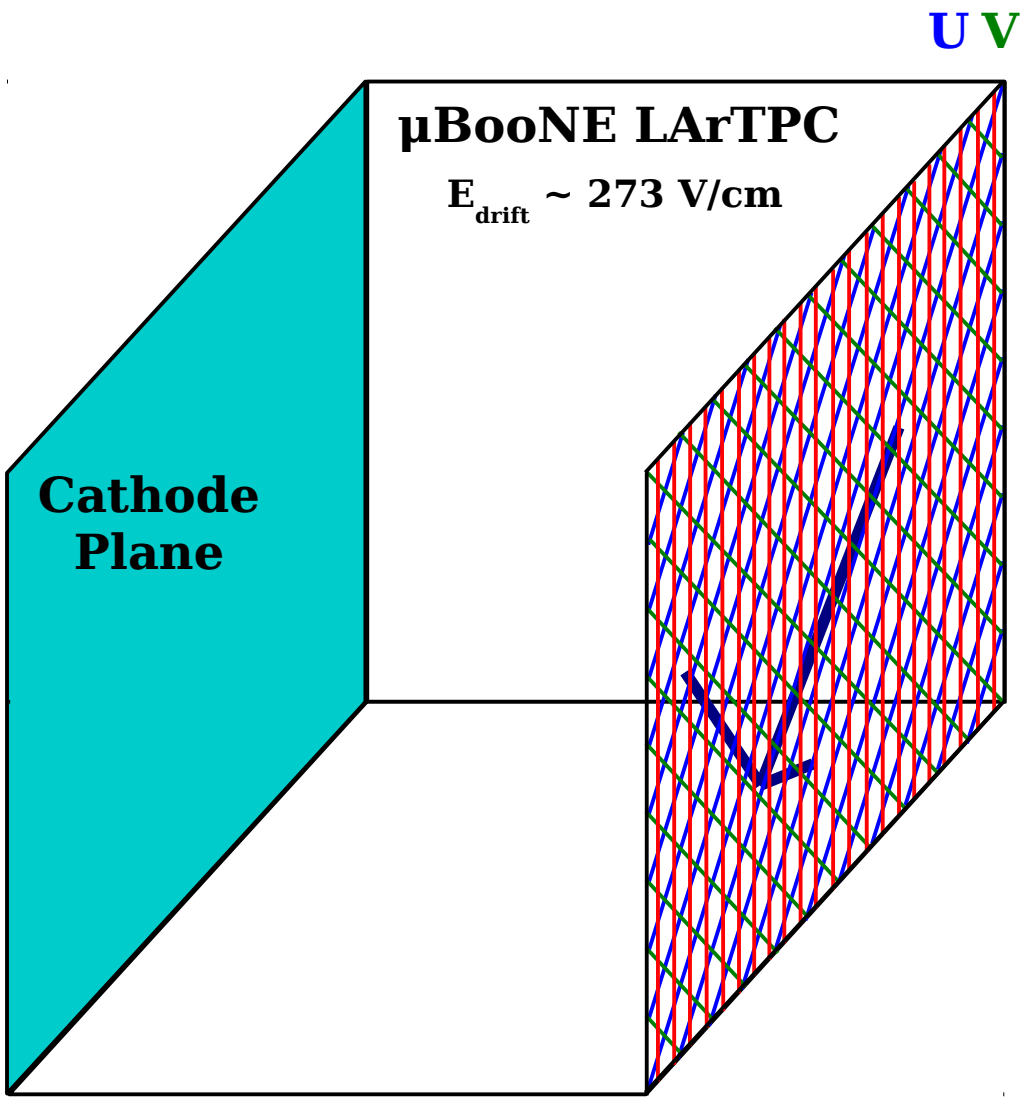

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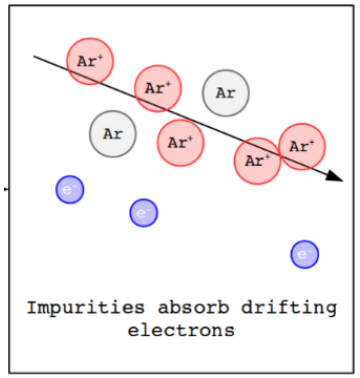
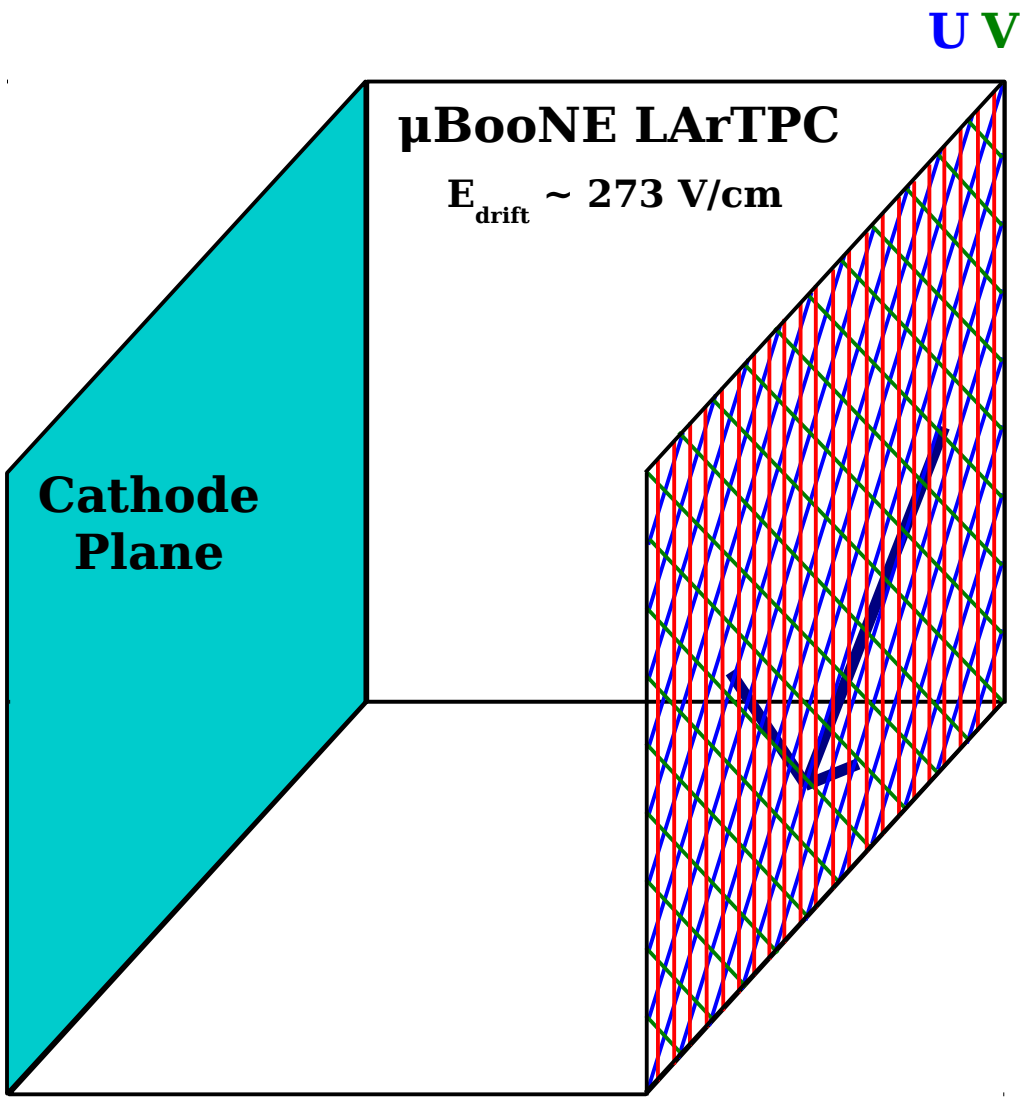
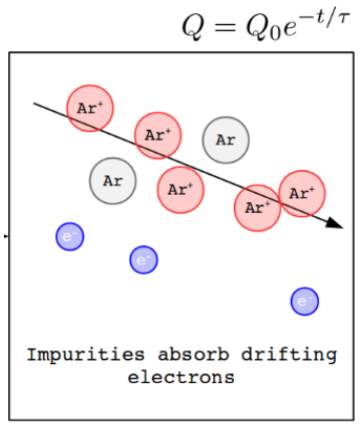
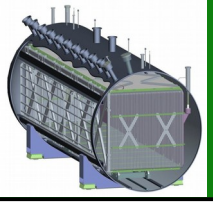


Signal Formation

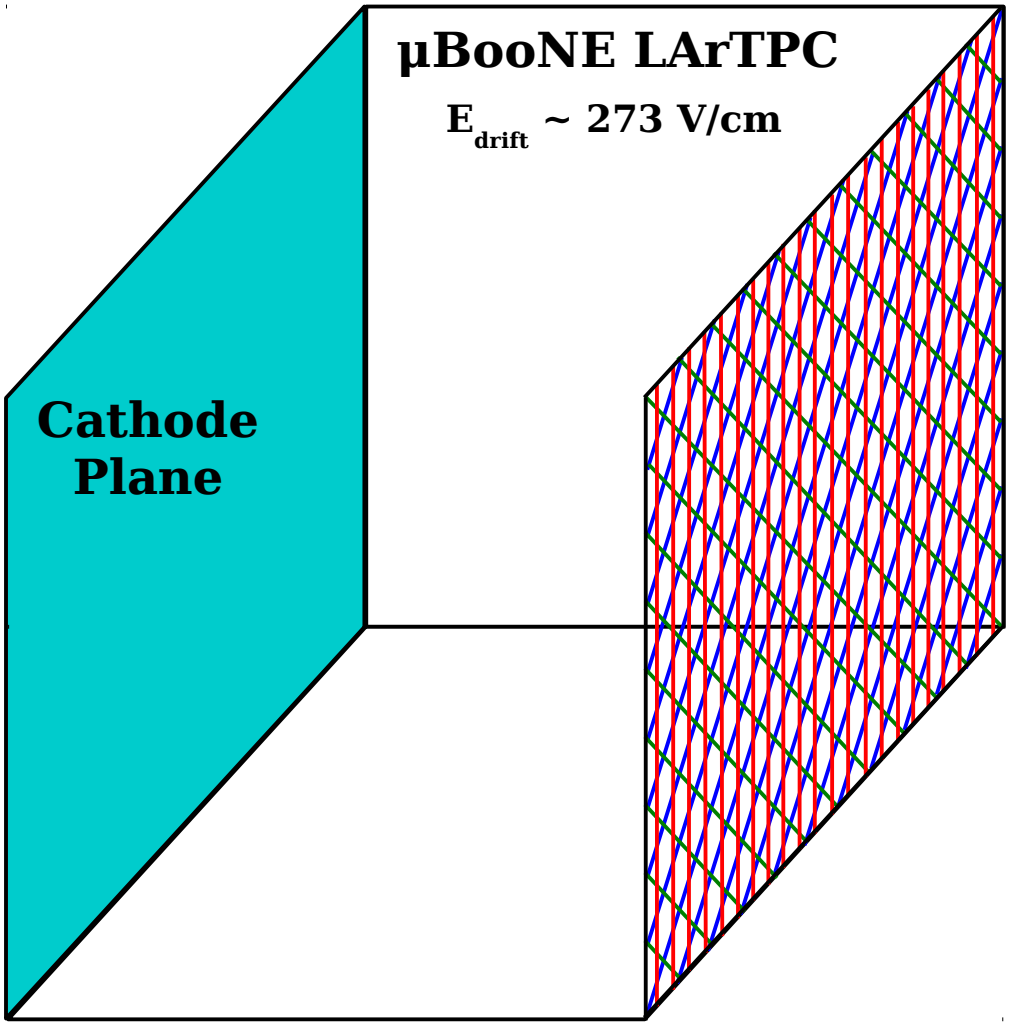


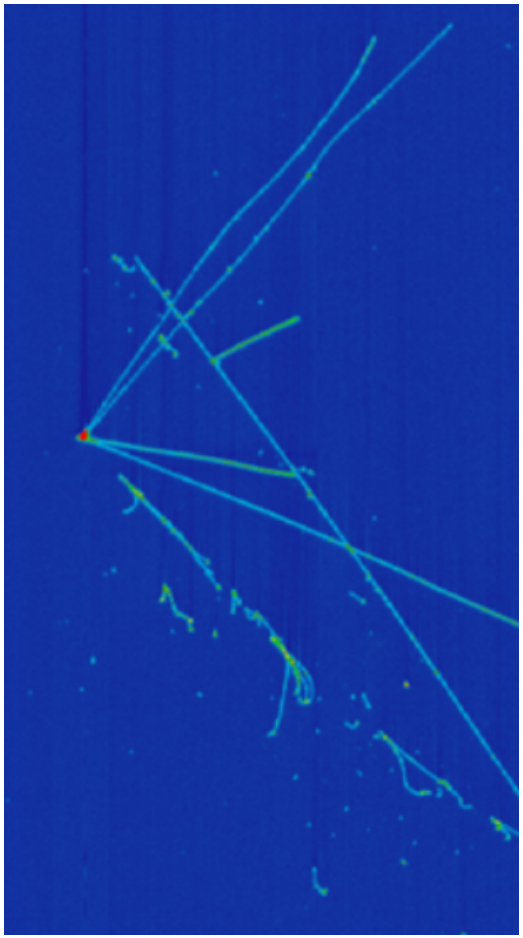




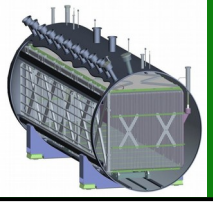
Signal Formation

U V Y

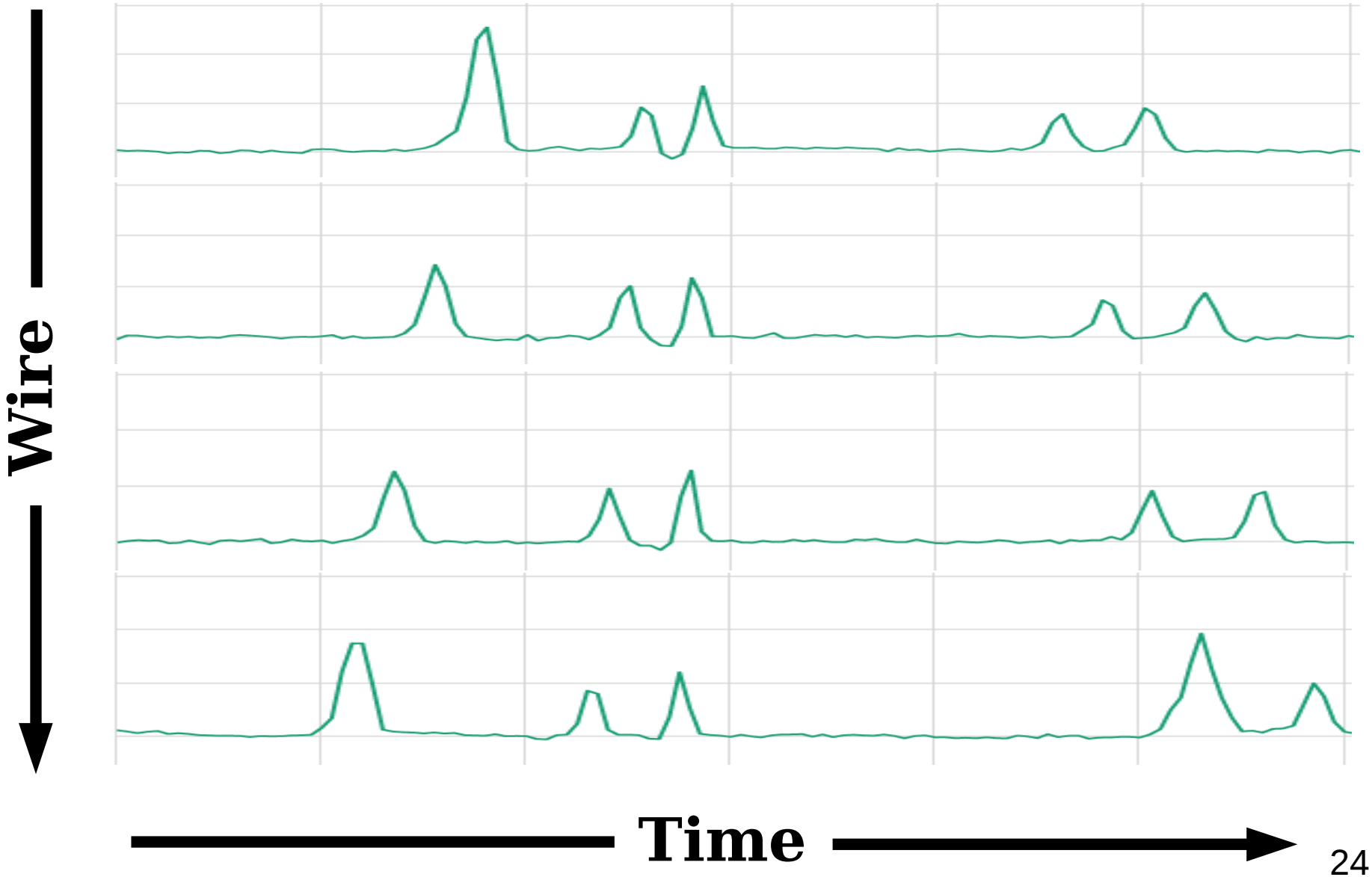


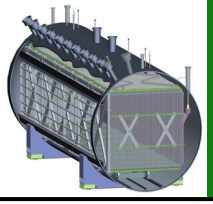


Three Images (One Per Wire Plane)

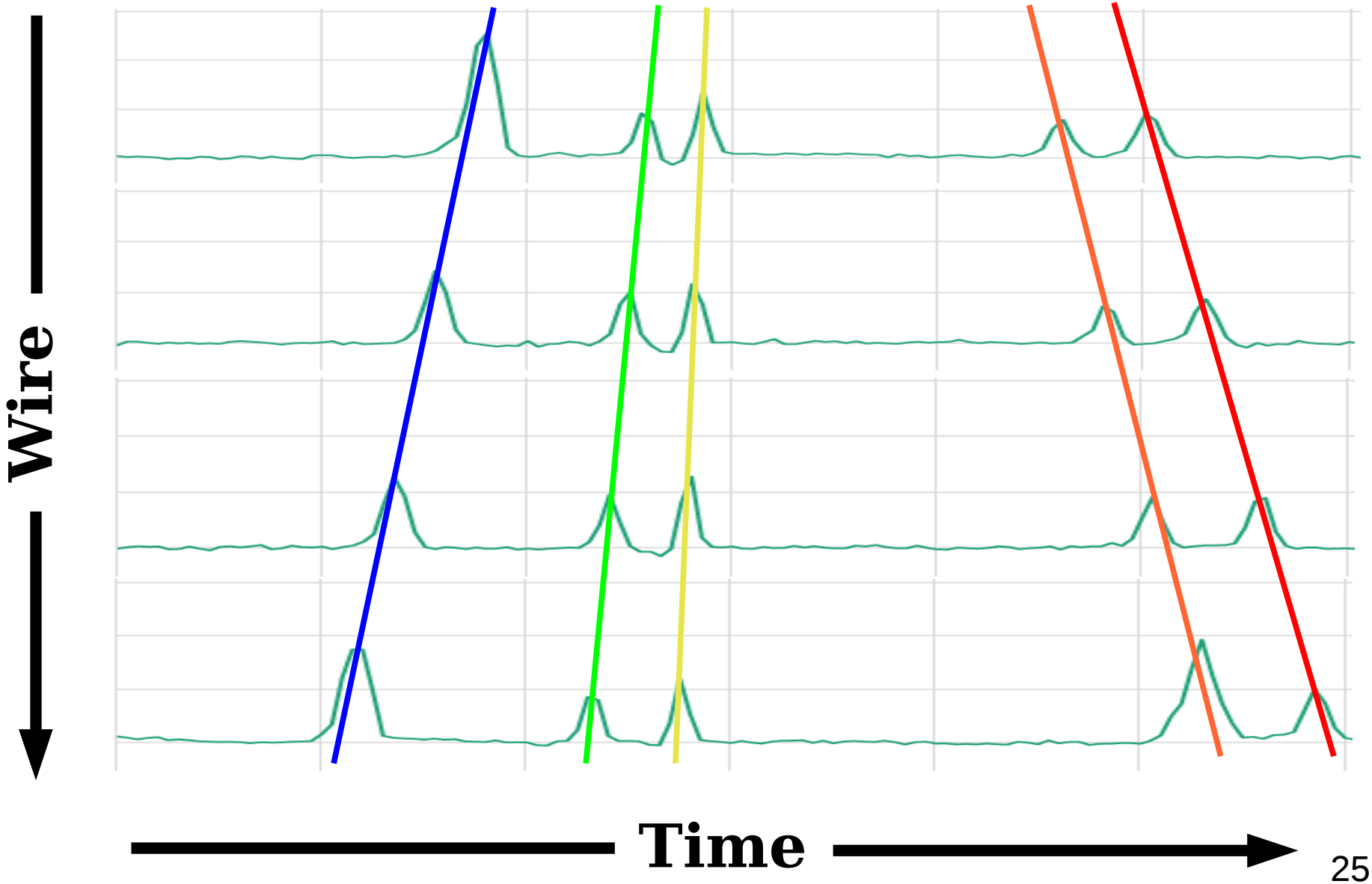


Raw Waveform Output

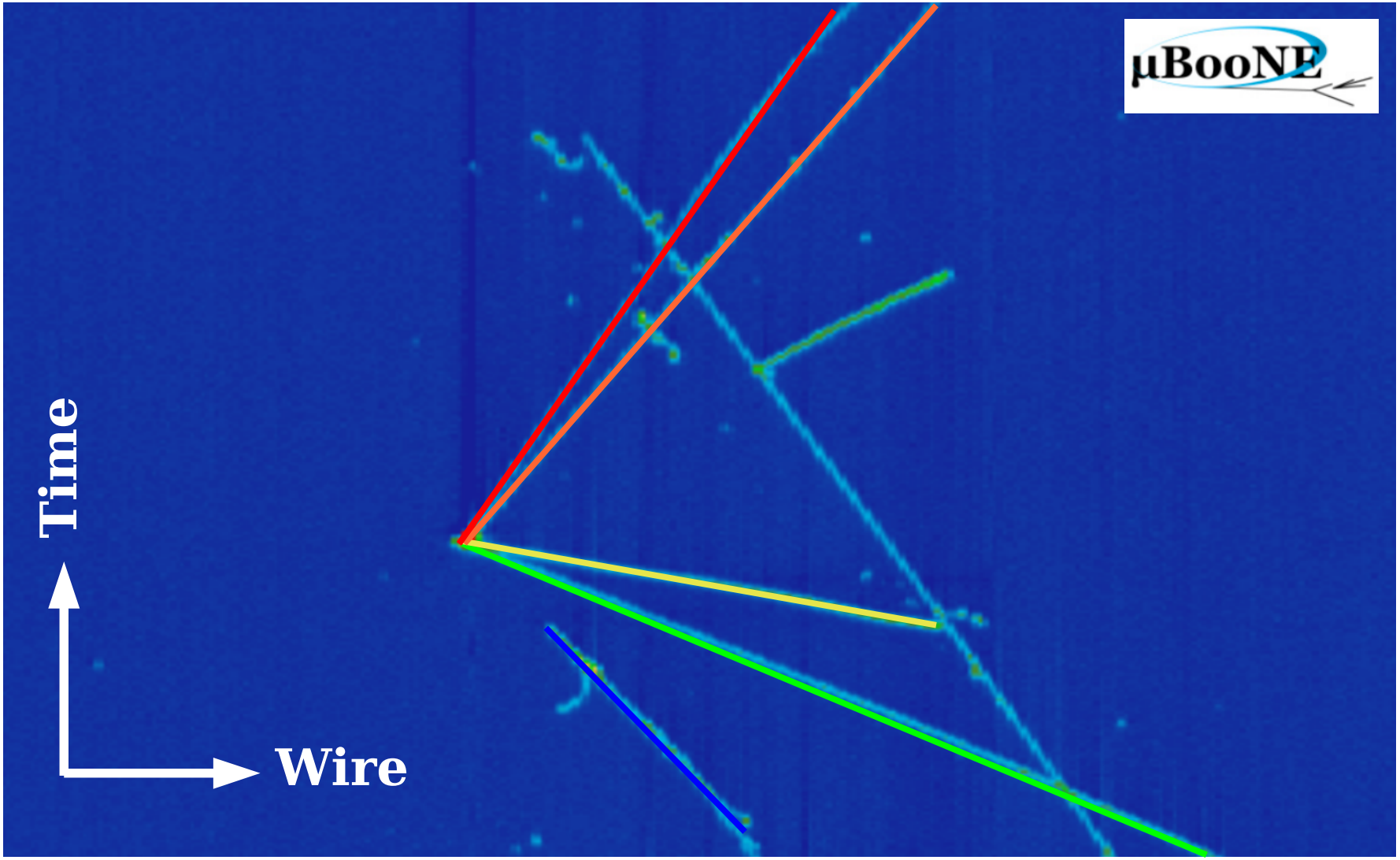




Raw Waveform Output

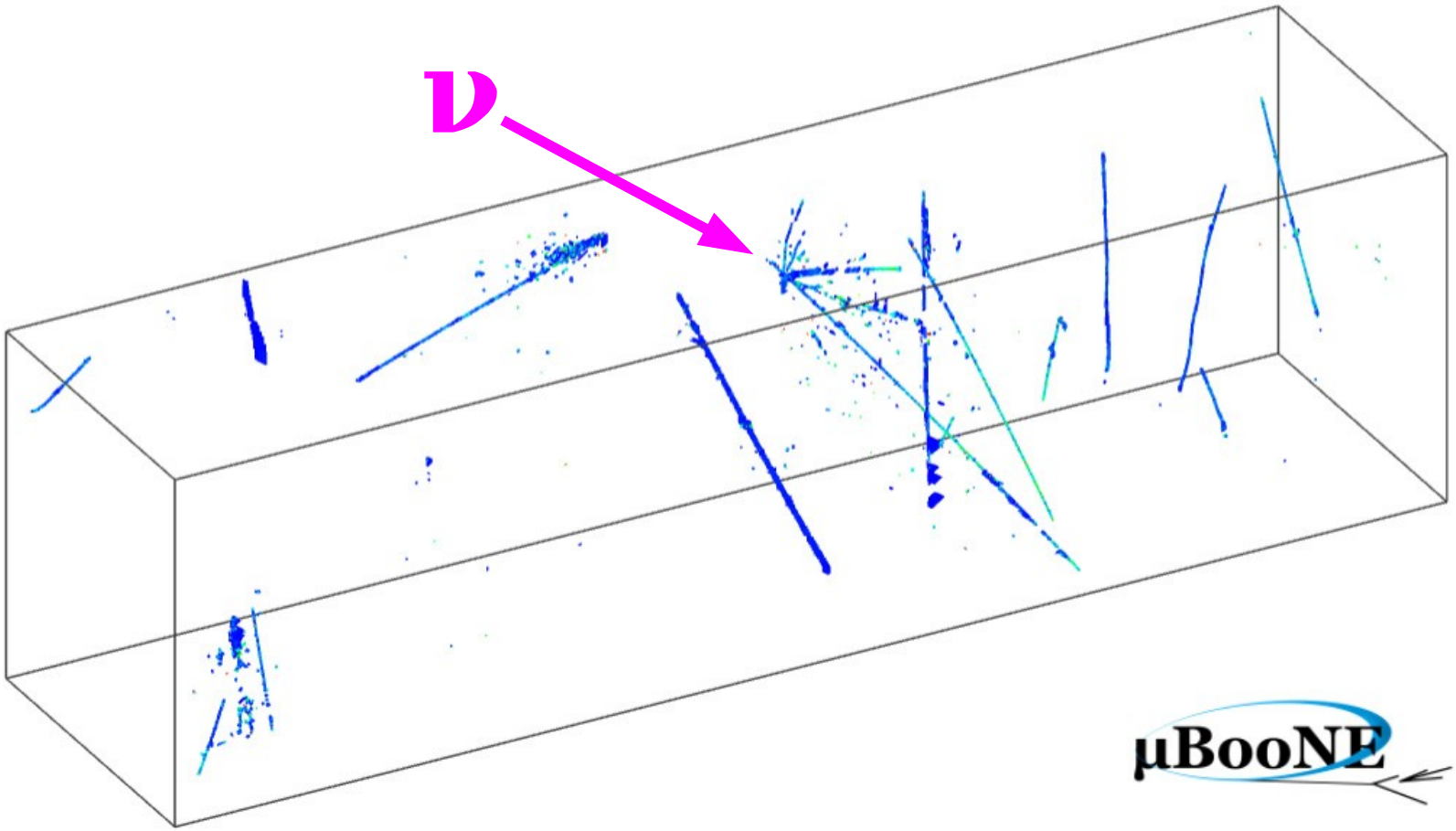


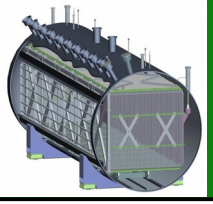
LArTPC Imaging



3D Event Reconstruction

- Combine two/three 2D wire plane views → reconstruct event in **3D**
  - Below: **neutrino interaction** event from **data**





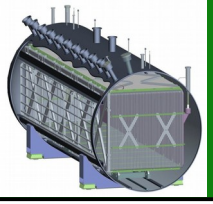
Workshop Summary

Workshop Organization

Day 1: Calibration (One West)

Day 2: Reconstruction (Hornet's Nest)

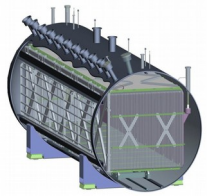
- Two days of workshop: LArTPC calibration (Monday, Dec. 10th) and LArTPC reconstruction (Tuesday, Dec. 11th)
- First day in One West, second day in Hornet's Nest



Workshop Topics

Calibration (Day 1)	Reconstruction (Day 2)
Low-Level TPC Calibrations	**Low-Level TPC Reconstruction**
Photodetector Calibrations	**Photodetector Reconstruction**
Calibration Sources	**Particle Reco. – 2D→3D Approach**
High-Level Calibrations	**Particle Reco. – 3D-only Approach**
DUNE Calibration Needs	**Particle Reco. – Deep Learning Approach**
	High-Level Reconstruction

- Topics generally moved from “low-level” to “high-level” as each day progressed
- Will summarize calibration and reconstruction topics together as opposed to separately

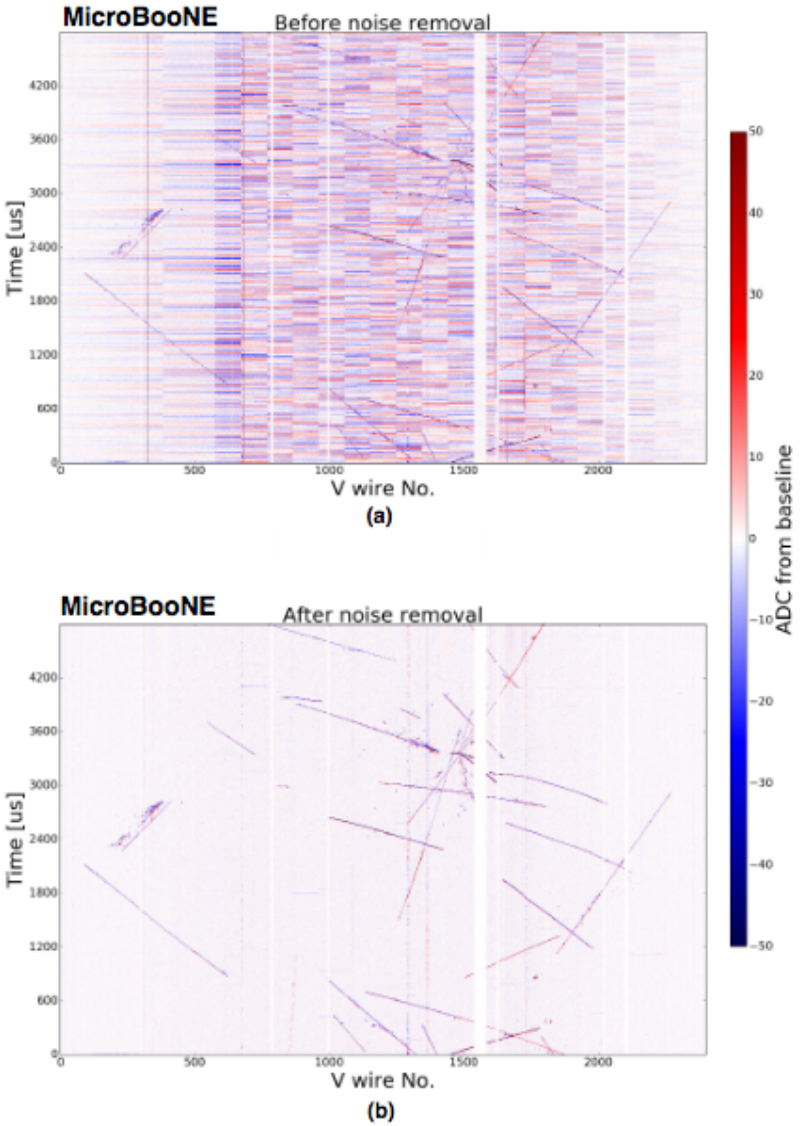


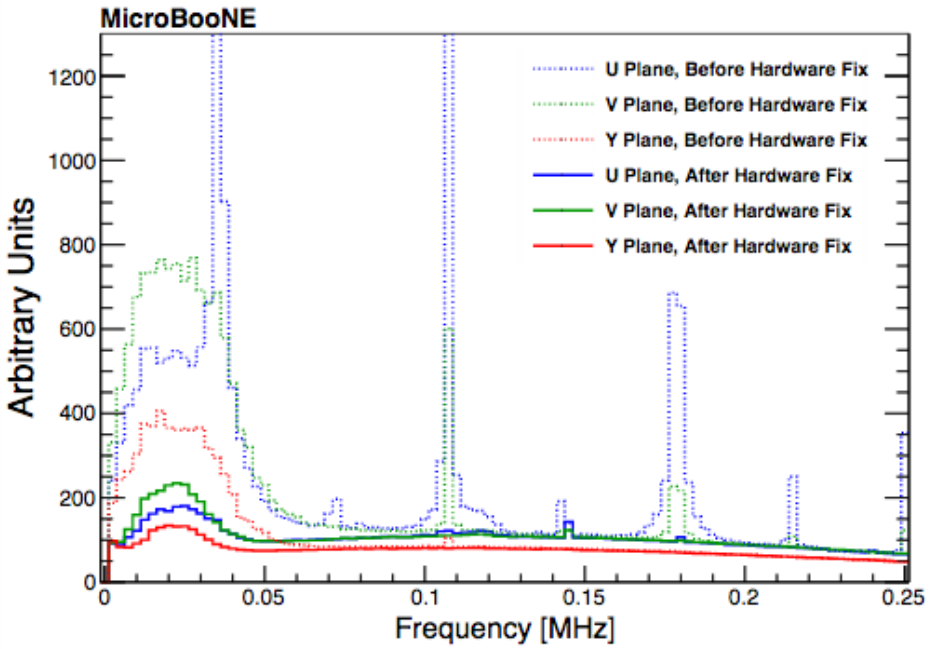
Outline

- **Low-Level TPC Calibrations/Reconstruction**
- Photodetector Calibrations/Reconstruction
- Particle/Event Reconstruction
- Calibration Sources
- High-Level Calibration/Reconstruction
- Needs for SBN and DUNE

TPC Noise @ μBooNE

M. Mooney

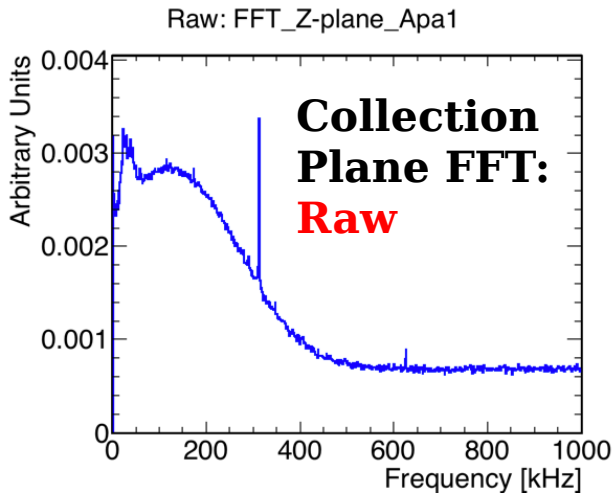


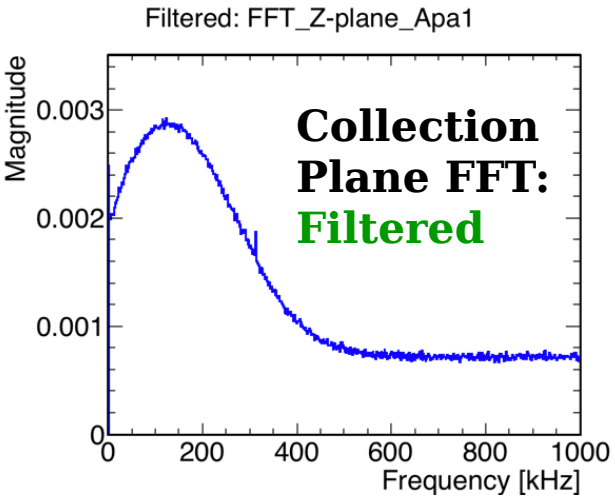


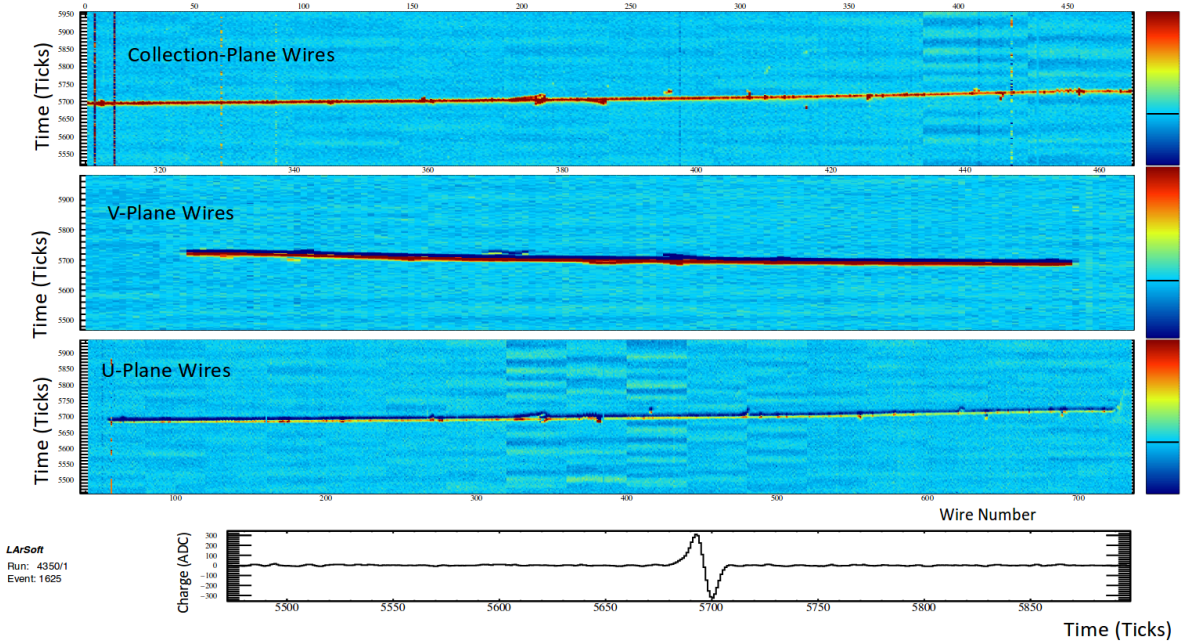
- MicroBooNE originally had excess noise “out of the box”
- Developed software noise filtering scheme – virtually gone
- Also addressed in hardware

TPC Noise @ ProtoDUNE-SP

M. Mooney







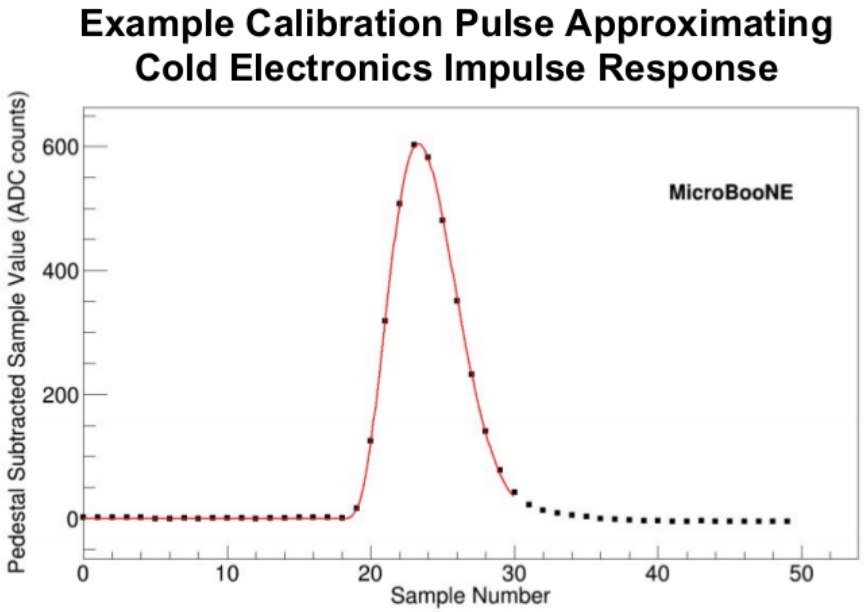
– Less than 0.3% dead channels

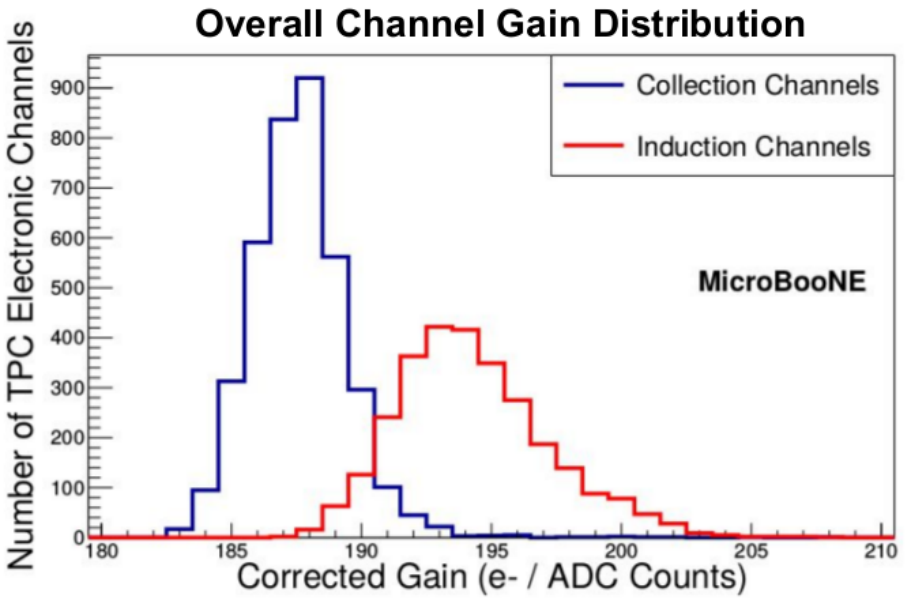
– Noise levels 500 (600) e^- for collection plane and 600 (700) e^- for induction planes after (before) <u>minor</u> coherent noise removal

- Much less noise “out of the box” – largely thanks to lessons learned from MicroBooNE experience!

FE Electronics Response

B. Kirby

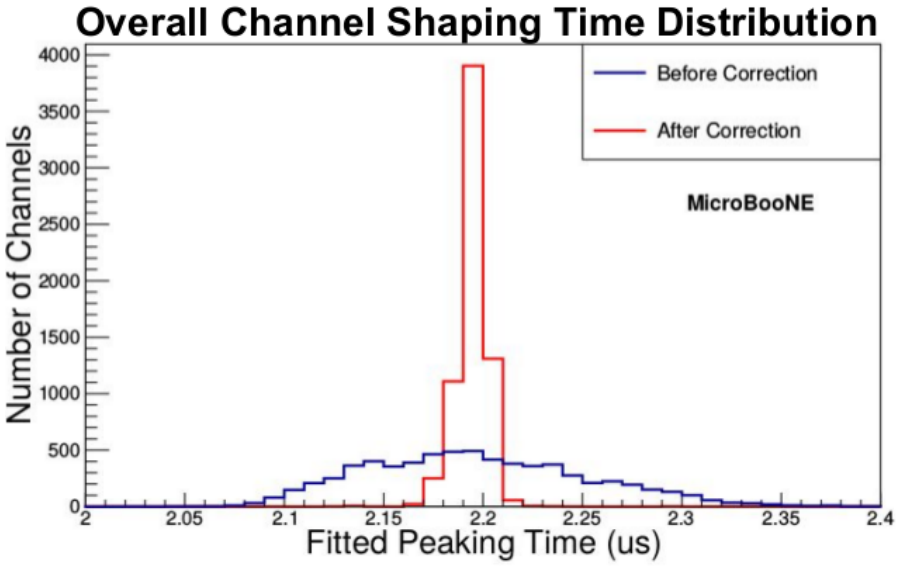


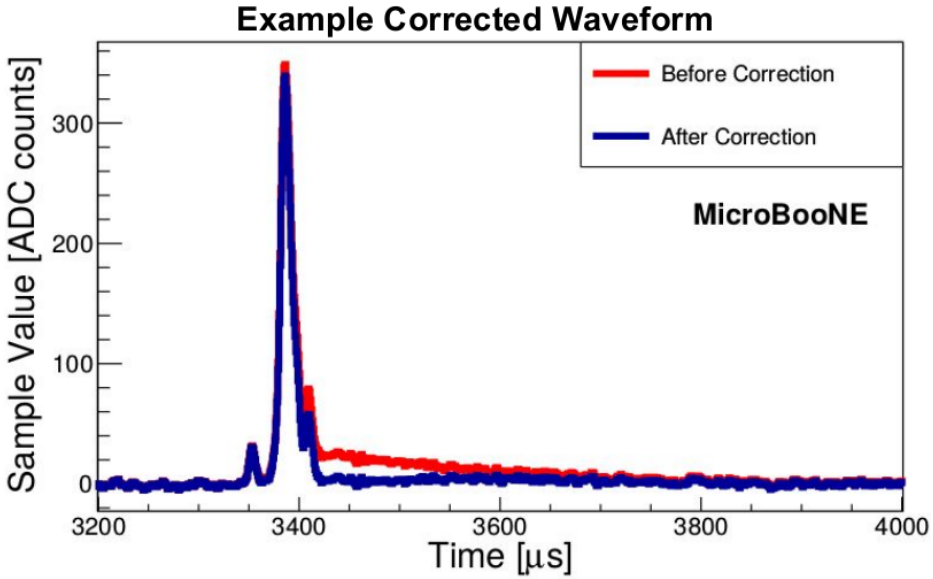


- Calibrate **gain and shape** of front-end (FE) electronics channel response using charge injection (internal or external) and per-channel coupling capacitor in FE ASIC
- Chanel-to-channel relative gain at µBooNE known to **2%**
- Non-ideal shape features calibrated out as well

FE Electronics Response

B. Kirby





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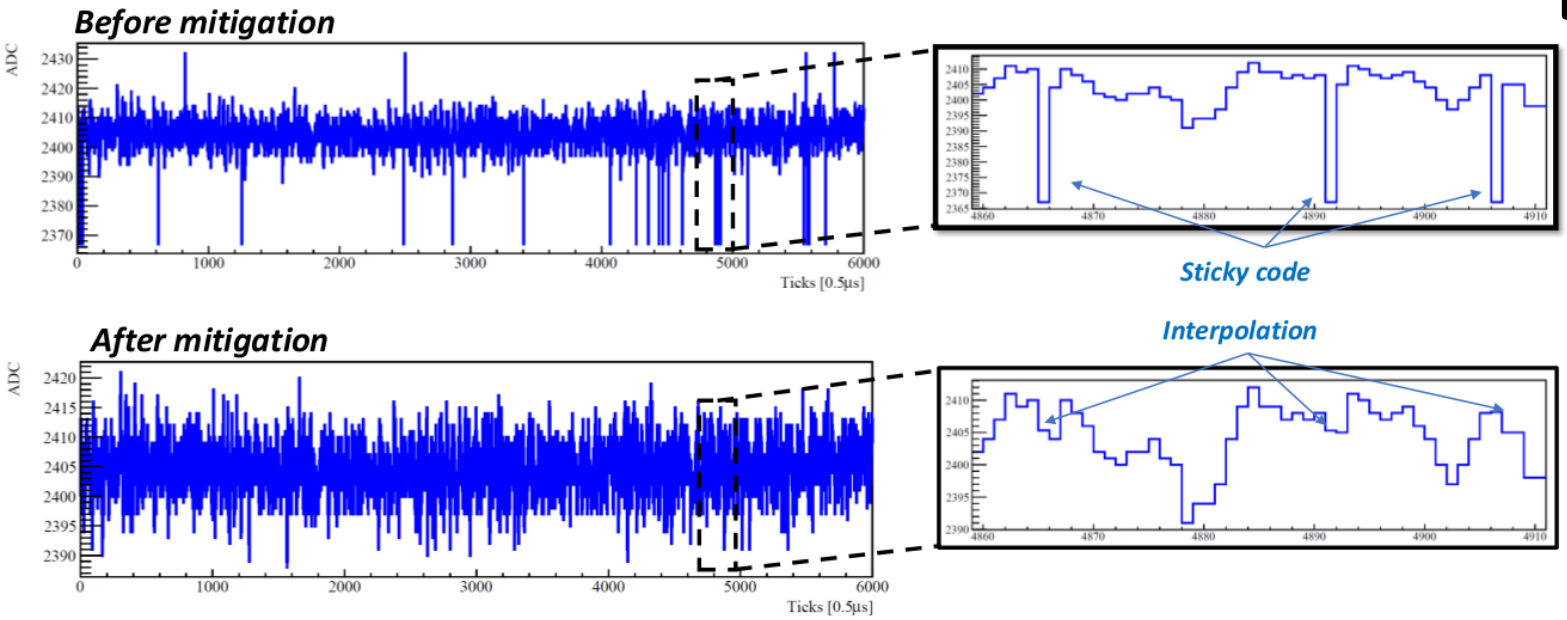
ADCs @ ProtoDUNE-SP

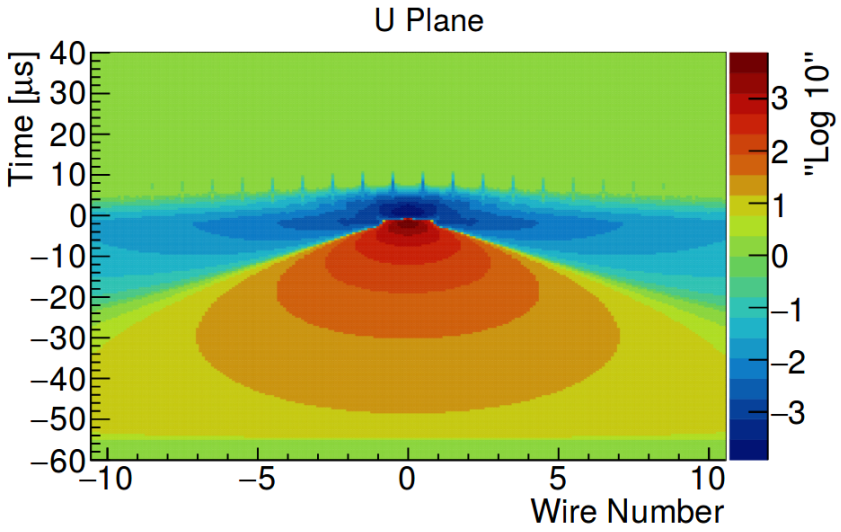
W. Gu

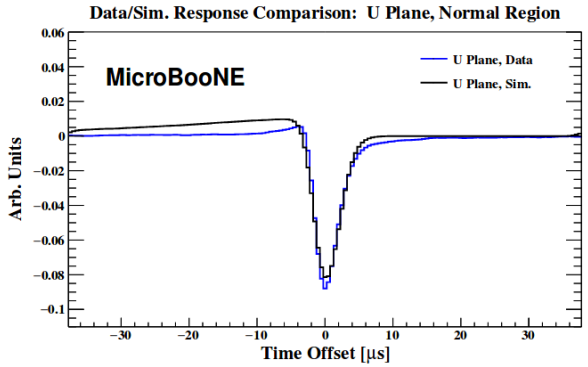


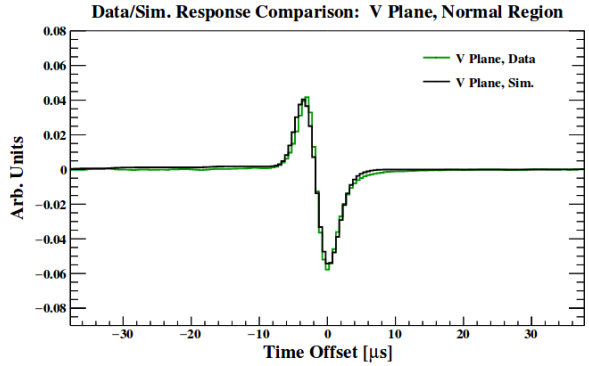
- ADC ASIC design at ProtoDUNE-SP has two problems:
  - (1) non-negligible nonlinearity; (2) “sticky codes”
  - Large effort ongoing to redesign for DUNE far detector
- Can mitigate both problems at ProtoDUNE-SP with dedicated calibrations
  - Identified need to estimate impact on charge resolution

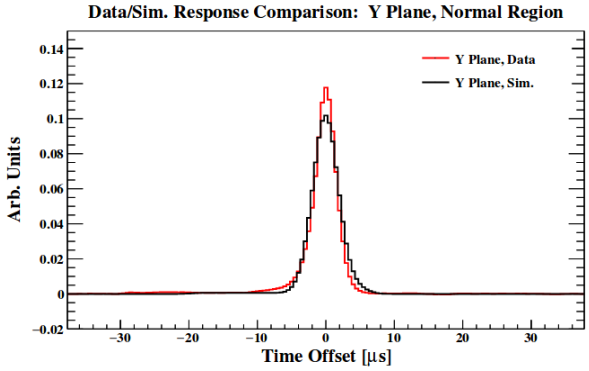
Wire Field Response

H. Wei





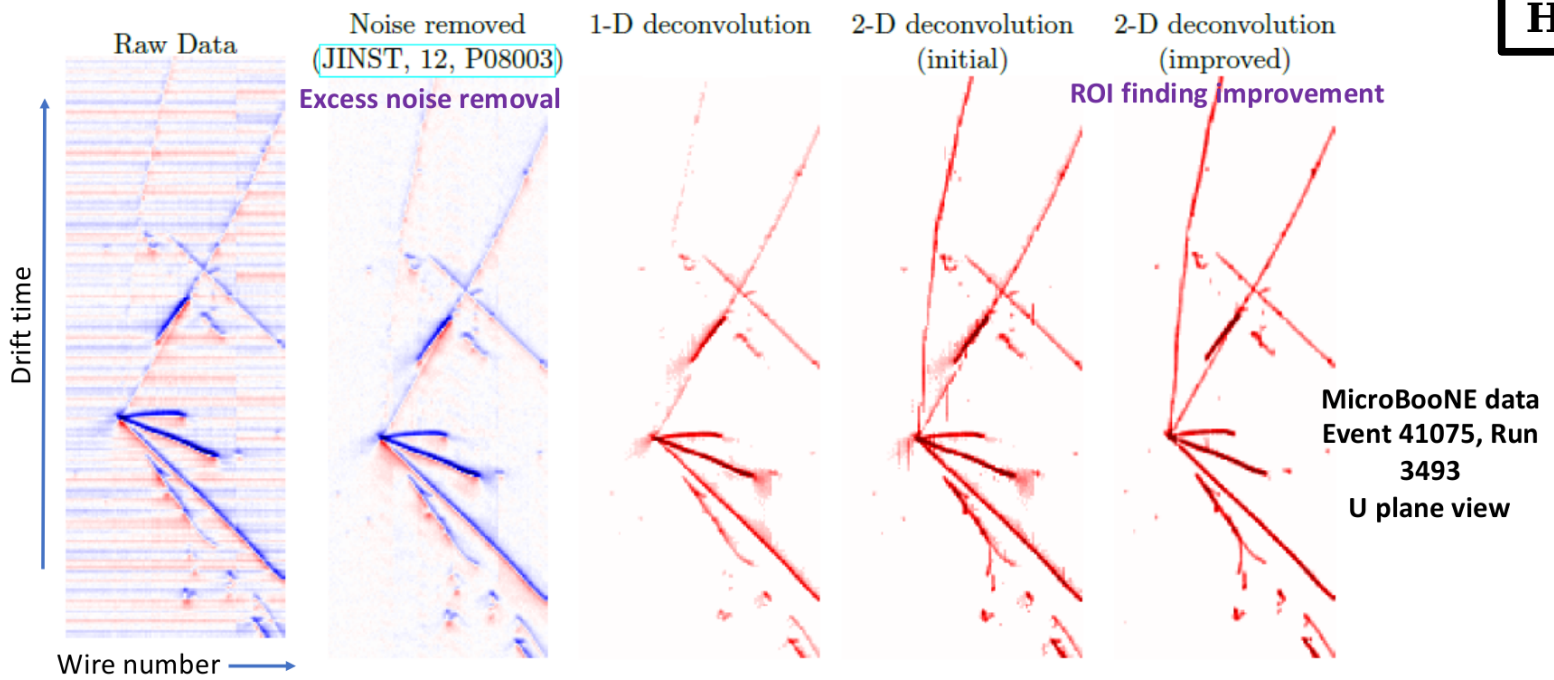




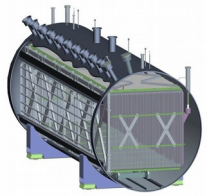
- Wire field response: response of wire to drifting ionization cloud
- **New simulation** accounts for 2D effects (charge induced on neighboring wires) at μBooNE
  - To be ported to other experiments
- Data/MC comparisons have minor discrepancies → measure w/ data?

2D Deconvolution

H. Wei



- Deconvolution: raw signal → measured charge
  - Deconvolution "divides out" response in frequency domain
  - 2D deconvolution: accounts for charge induced on nearby wires (even far away from "principal" wire… ±10 wires!)
- 2D deconvolution *greatly improves imaging* at μBooNE
  - Plan is to **port to other LArTPC experiments**



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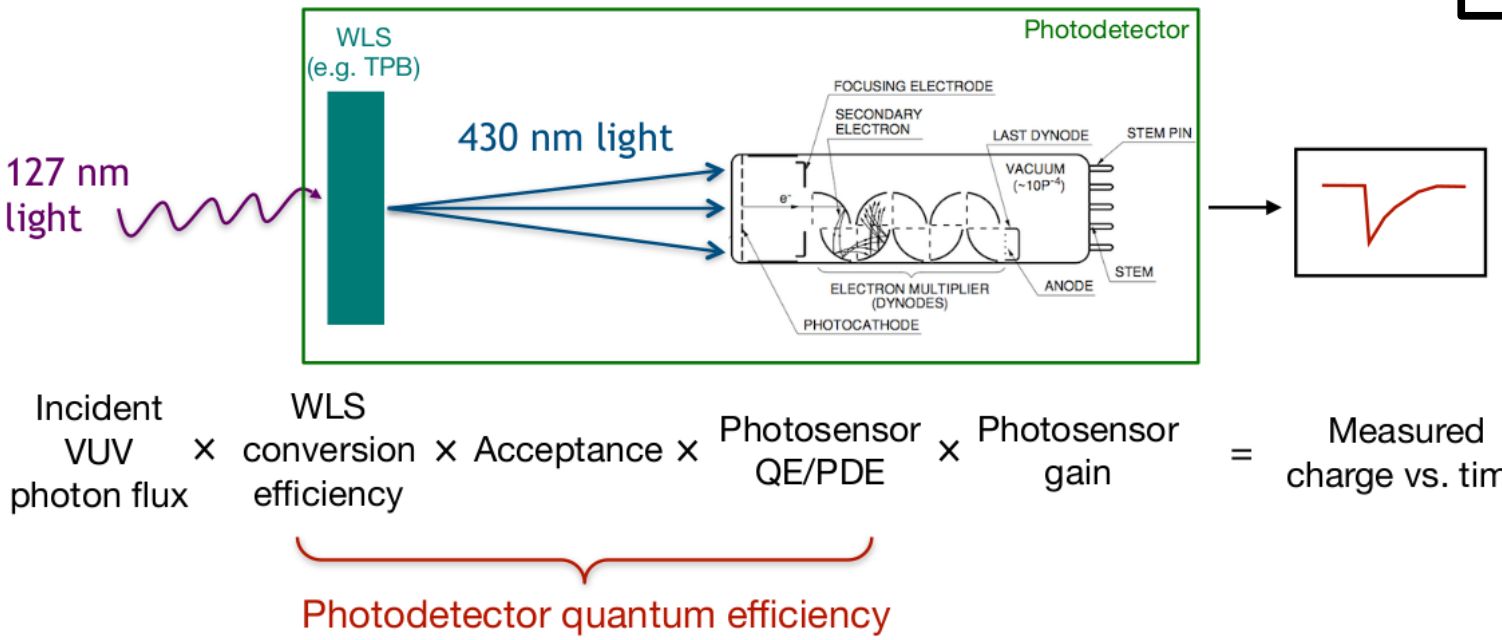
PDS Gain, QE

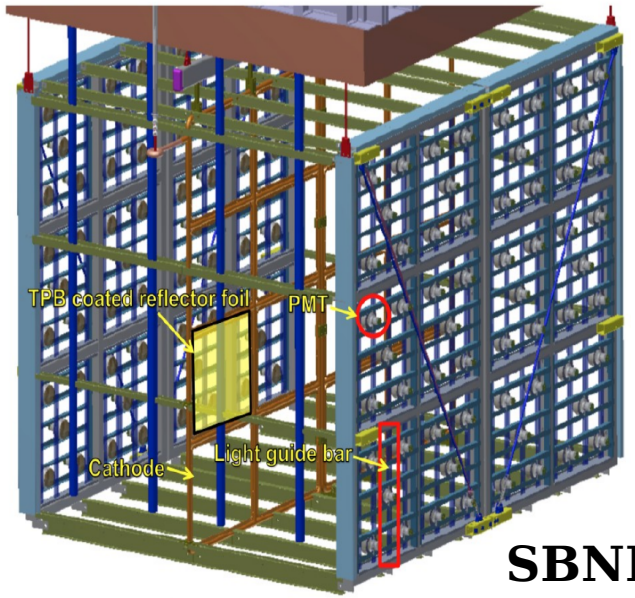
M. Toups



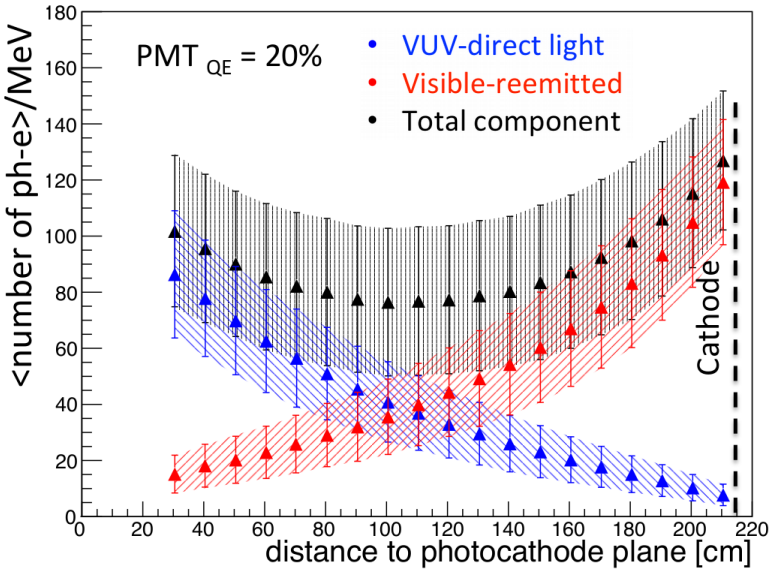
- Photon Detection System (PDS): use for triggering, timing
- Goal: infer incident VUV photon flux from measured signal
  - Use single photoelectron (PE) scintillation signal to monitor changes in gain over time (e.g. from ^{39}Ar beta decay)
  - Could rely on test stands to validate predictions of quantum efficiency (QE) from simulation

Light Yield @ SBND

D. Garcia-Gamez



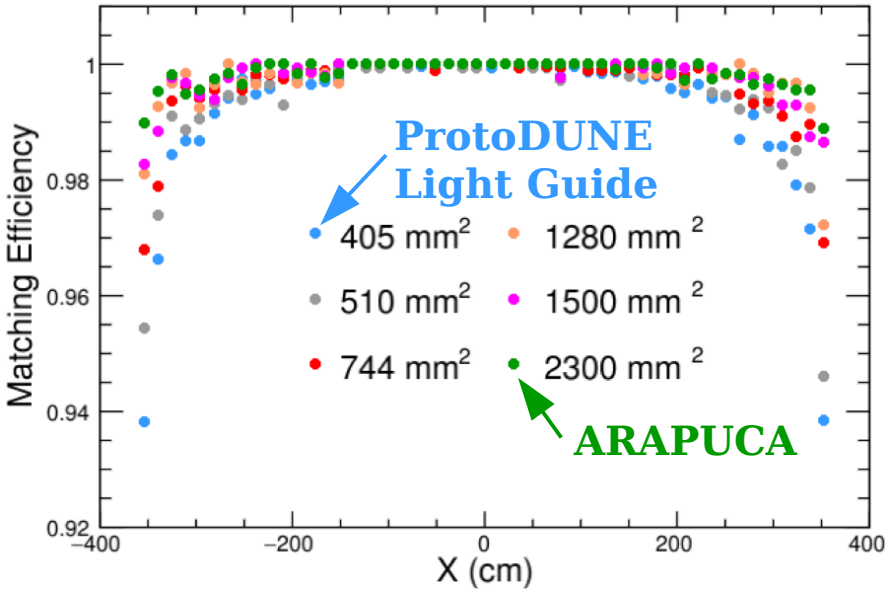
SBND

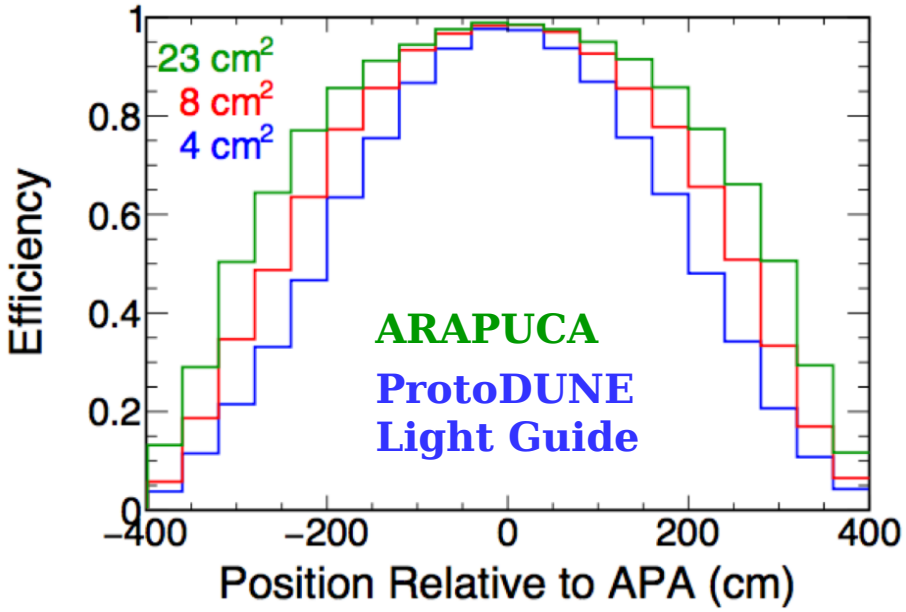


- SBND exploring use of reflector foils to increase light yield
- Lower light yield near cathode → may not trigger on low-energy events near cathode (e.g. supernova neutrinos)
  - Mitigate with wavelength-shifting reflector foils on cathode
  - Test at SBND, possibly use for DUNE far detector?

Flash Matching @ DUNE

A. Himmel



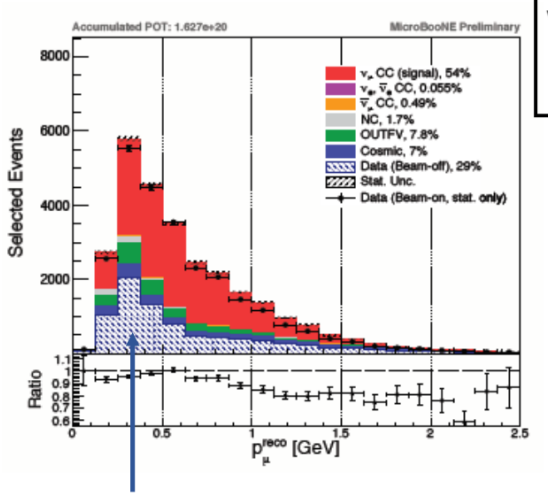


- DUNE exploring different PDS designs
- One metric: capability of correctly matching light “flash” in PDS to associated ionization signal
- Preliminarily, ARAPUCA seems to perform better (larger effective area) for proton decay, supernova ν physics

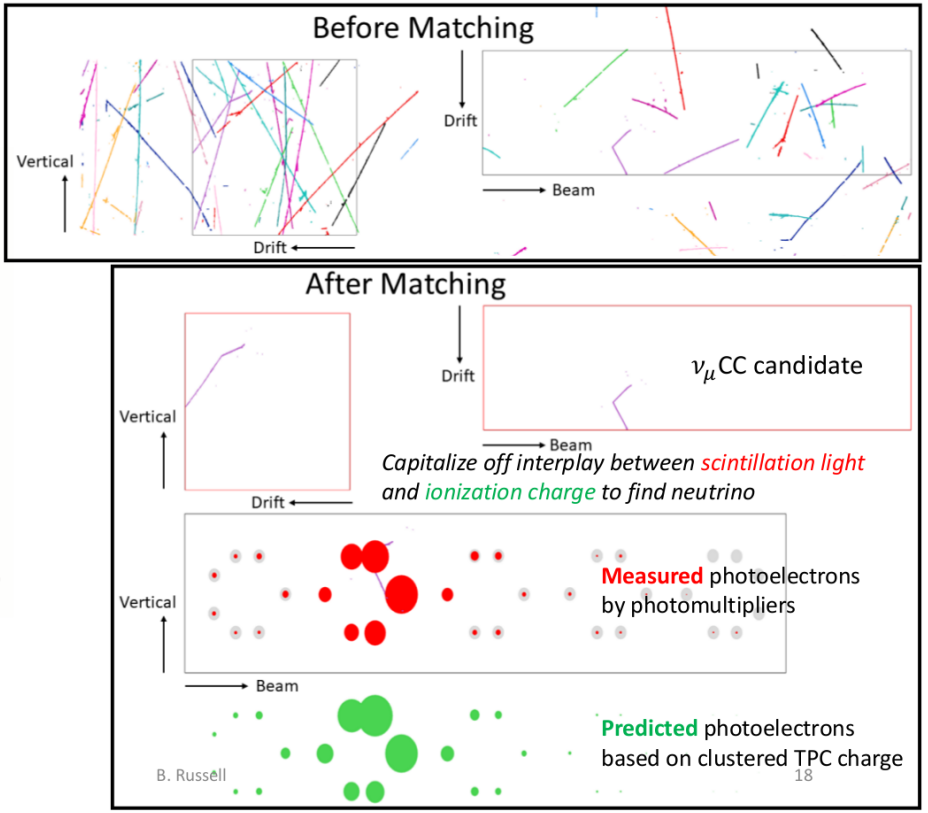
Flash Matching @ μBooNE

B. Russell

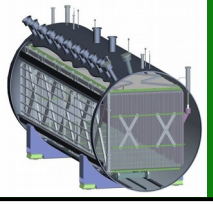
Contending with near-surface operation



For first generation physics analyses, cosmic rays were the leading backgrounds



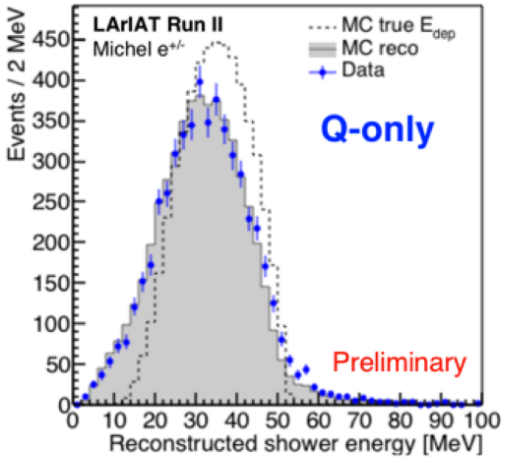
- Cosmogenic background mitigation at μBooNE with "many-to-many PMT flash-TPC cluster matching"
  - Associate every PMT flash with ionization activity in detector
  - Better neutrino candidate ID; useful for data reduction



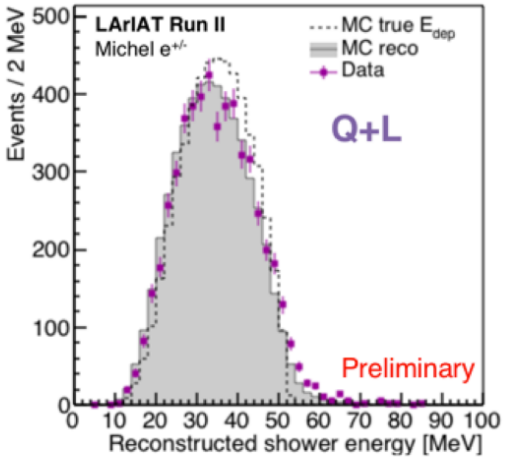
Energy Reco. w/ Light

W. Foreman

Q-only

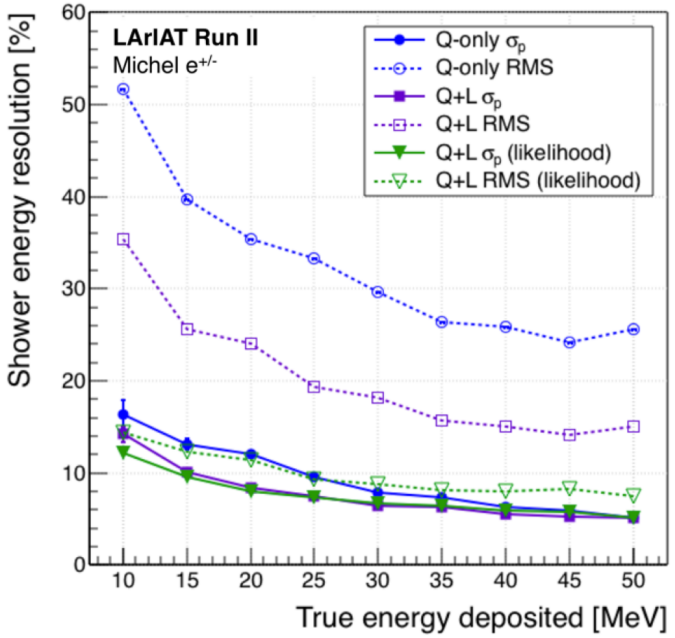


Q+L

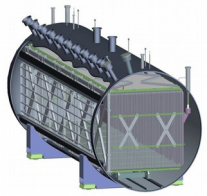


$$E = \frac{Q}{\langle R \rangle} \times W_{ion}$$

$$E = (Q + L) \times W_{ph}$$



- Use of PDS for energy reconstruction also being explored
- Improvement of **Michel electron energy reconstruction** by making use of both charge and light at LArIAT
- Very promising start – will be studied in context of many applications at DUNE (e.g. supernova/solar neutrinos)



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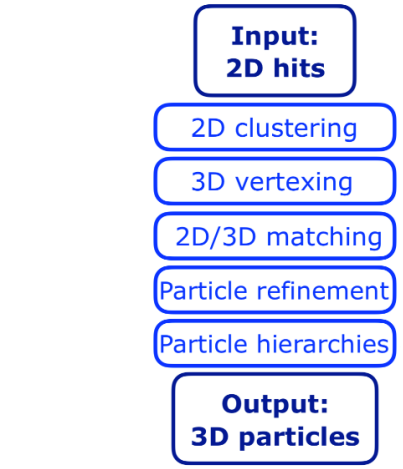
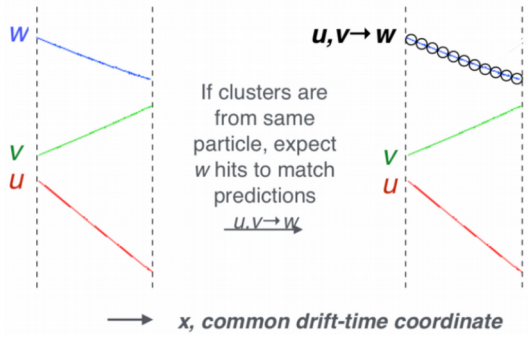
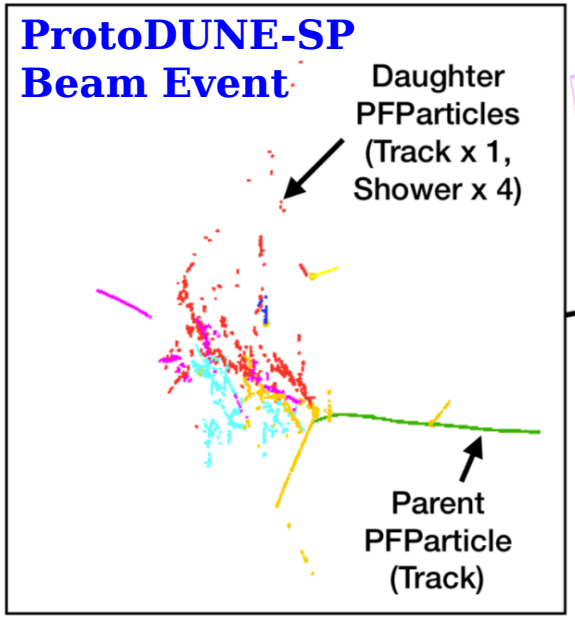
2D→3D Reco: Pandora

L. Escudero

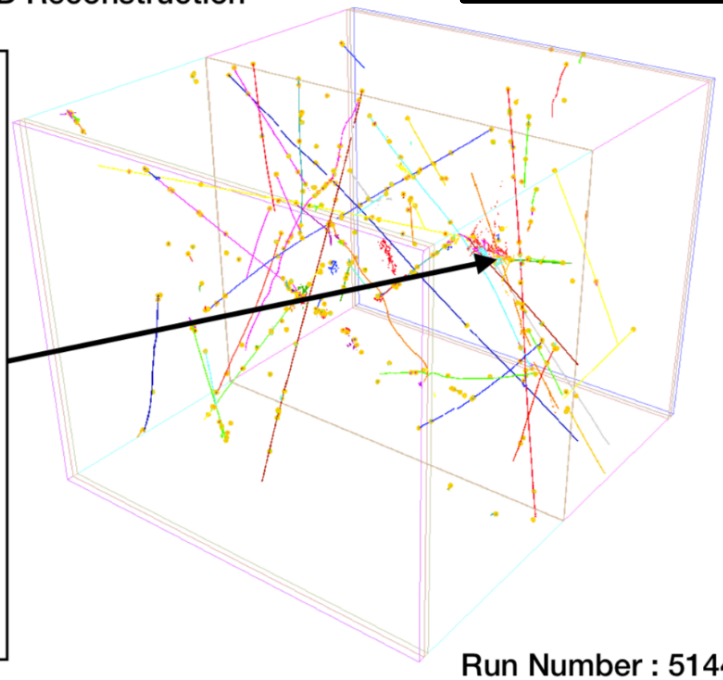






Default Pandora beam particle ID identifies this particle as a test beam pion automatically.

Full 3D Reconstruction



Run Number : 5144
Event Number : 47293
(--nskip 0)
np04_raw_run005141_0016_dl2.root

- Pandora Toolkit: multi-algorithm approach to complete event reconstruction, starting with 2D pattern recognition
  - Elevate to 3D by matching 2D views using shared time info
  - Used extensively at μBooNE; first results with ProtDUNE-SP

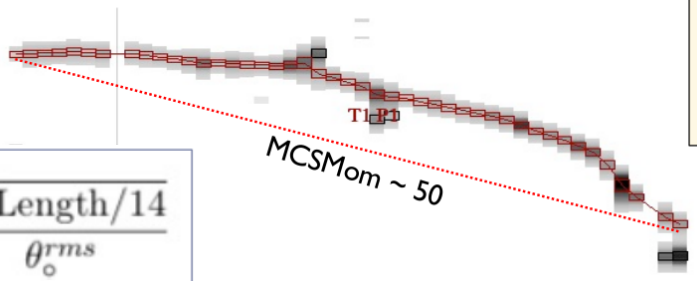
2D→3D Reco: TrajCluster

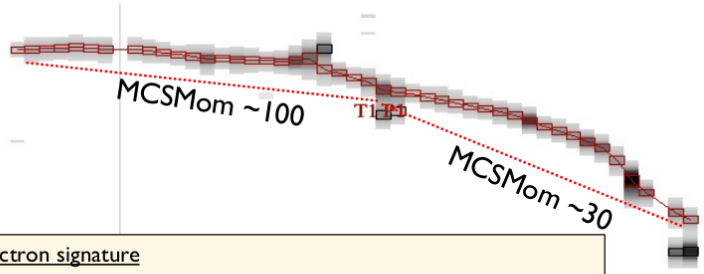
B. Baller

Tagging Electrons (< 100 MeV)

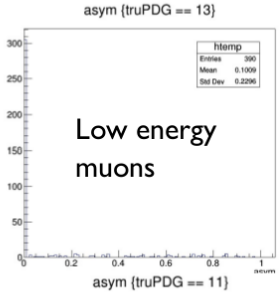
Work in Progress

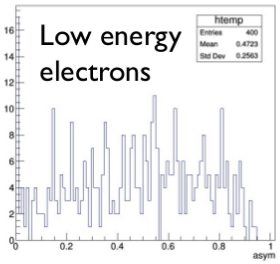
$$\text{MCSMom} = 13.8 \times \frac{\sqrt{\text{Length}/14}}{\theta^{rms}_{\circ}}$$





Requires precision reconstruction. Encouraging preliminary results on single electrons at small angle





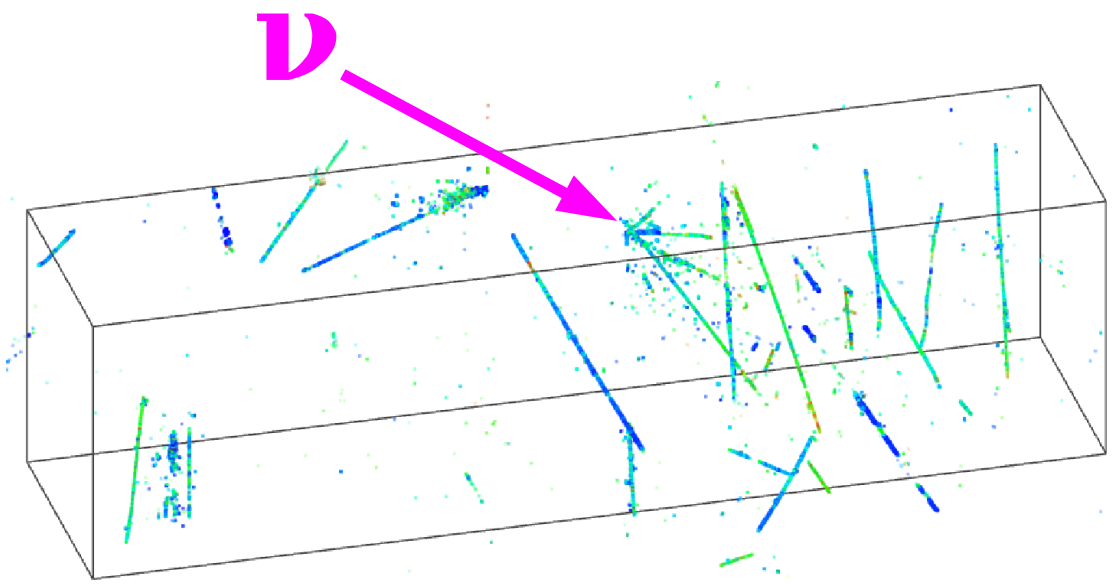
Electron signature
Start-end MCSMom asymmetry = (100 – 30) / (100 + 30) = 0.54
Charge rms = 0.43

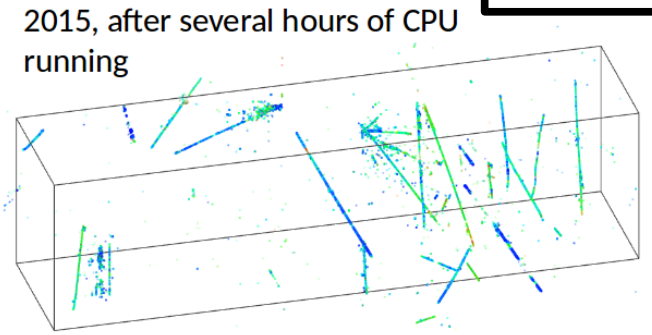
17

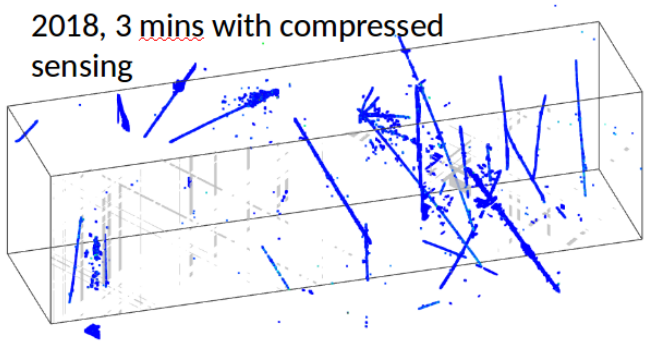
- TrajCluster: another 2D→3D method that makes heavy use of fine-grained "substructure" of particle topology
  - e.g. using Multiple Coulomb Scattering (MCS) to identify low-energy electrons (preliminary, but promising)

3D-only Reco: Wire-Cell

X. Qian



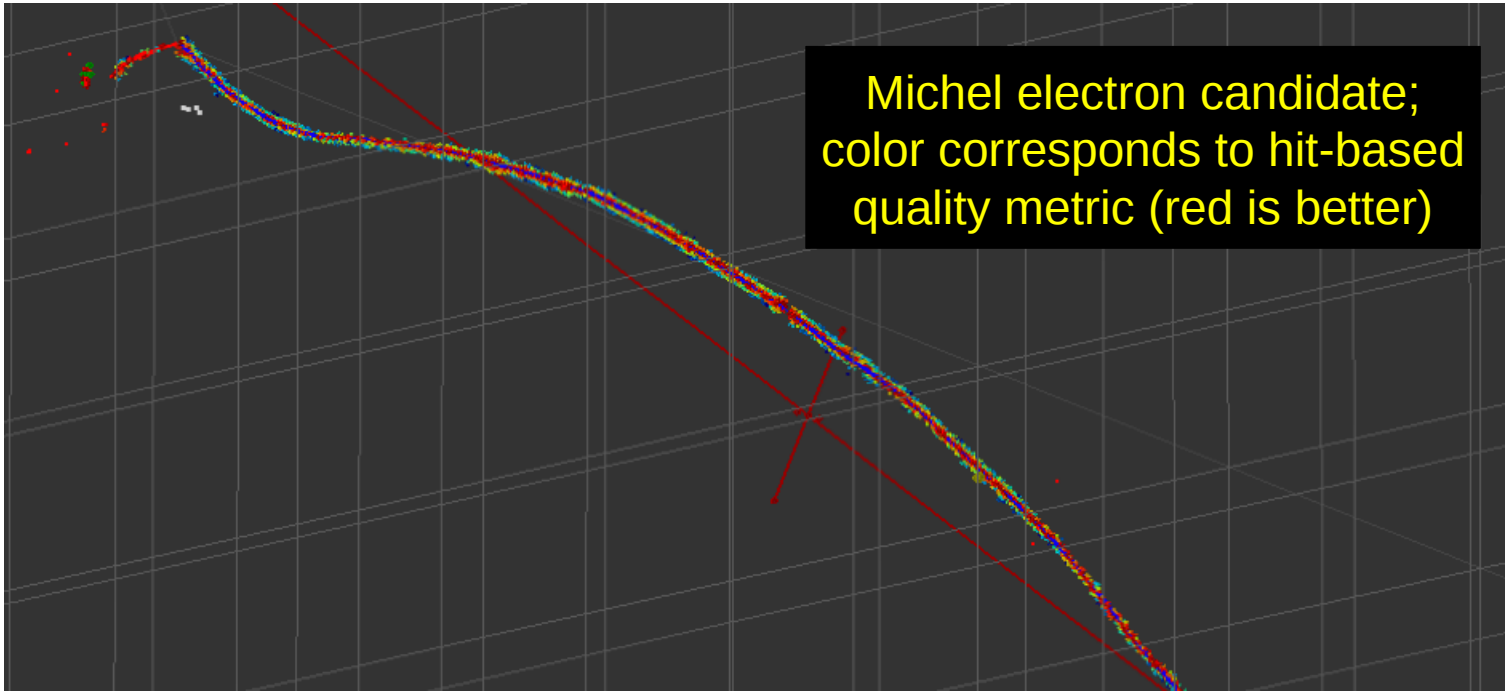




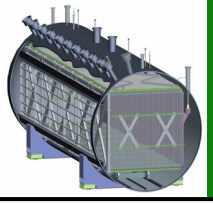
- Wire-Cell: uses **charge-matching** across three planes to form 3D image, then do 3D pattern recognition (no 2D)
  - Pattern recognition simpler in 3D – less ambiguities
  - Take advantage of sparsity of event data in 3D by applying compressed sensing techniques → imaging fast and robust

3D-only Reco: Cluster3D

T. Usher



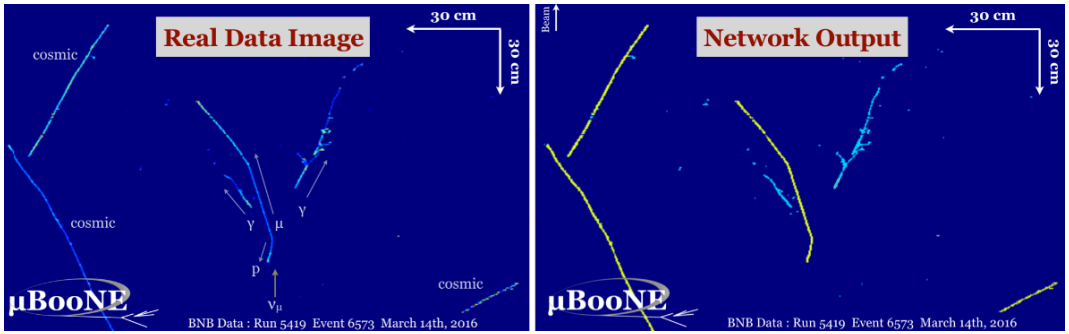
- Cluster3D: start with 2D hits (Gaussian fits of deconvolved TPC waveforms), then go directly to 3D hits
  - Still no 2D pattern recognition
  - Nice alternative approach to Wire-Cell with no use of charge; would be useful to compare two approaches



Deep Learning: Particle Reco.

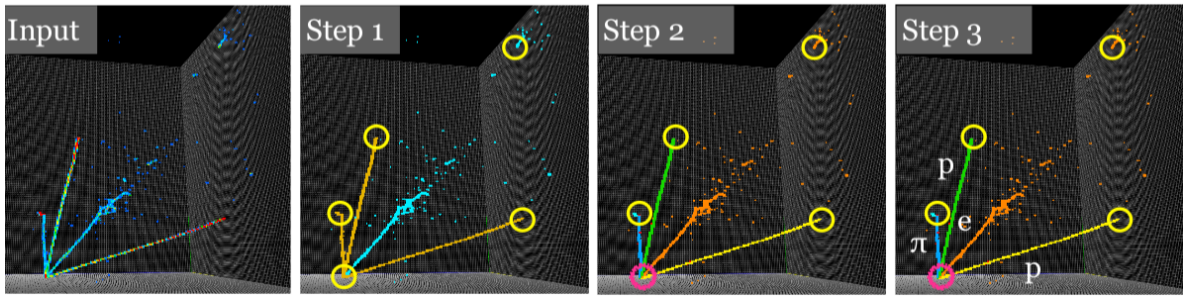
K. Terao

2D



3D

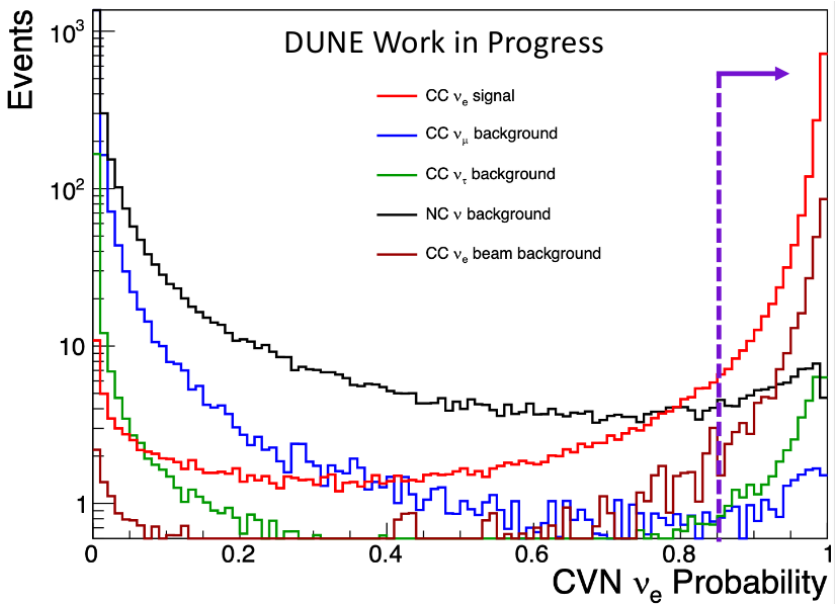
- [x] 1. Space point (track edges) + pixel feature annotation
- [x] 2. Vertex finding + particle clustering
- [x] 3. Particle type + energy/momentum
- [ ] 4. Hierarchy building

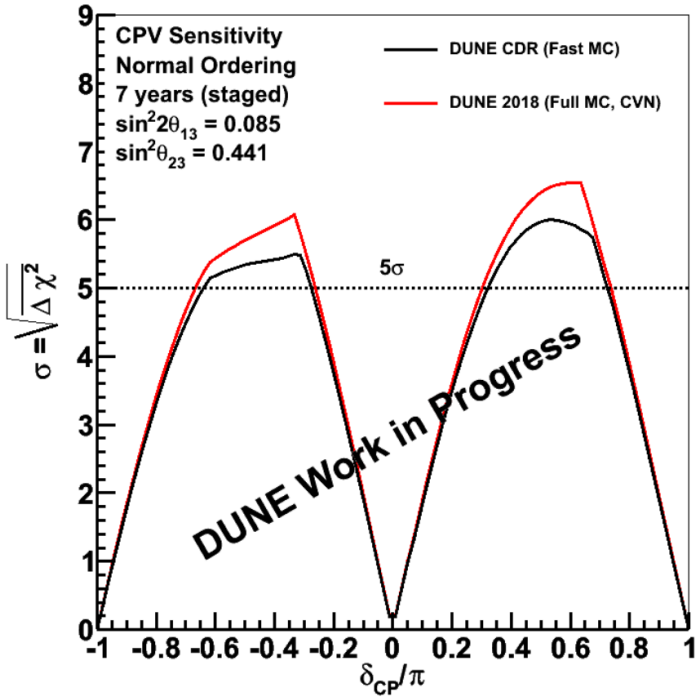


- Track/shower classification with CNN (Convolutional Neural Network) in 2D → **μBooNE paper**
- Now working on 3D space points as input – using sparse submanifold convolution (faster, scales better for 3D)

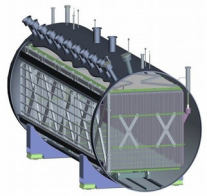
Deep Learning: Neutrino ID

L. Whitehead



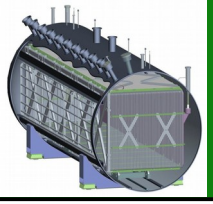


- Have also applied similar Deep Learning techniques to identify neutrinos at DUNE far detector in MC studies
- CP violation sensitivity has improved over DUNE CDR result, despite more careful treatment of systematics



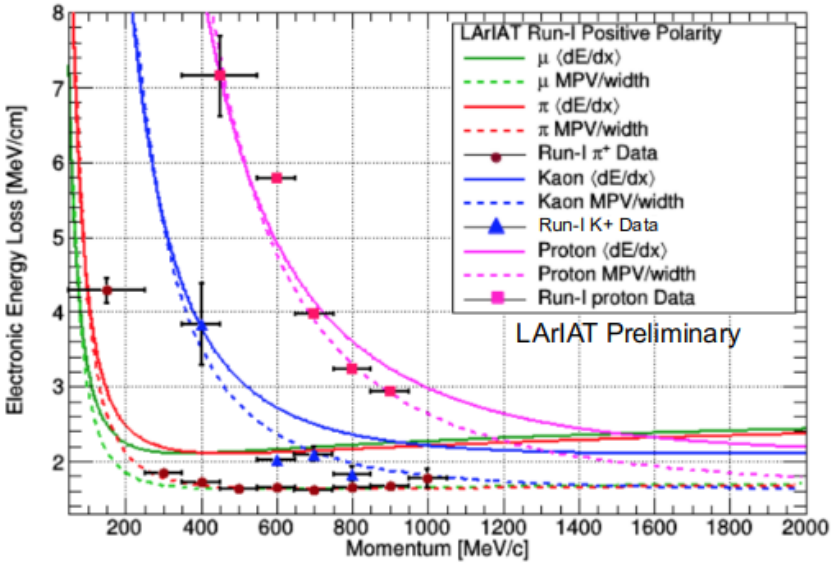
Outline

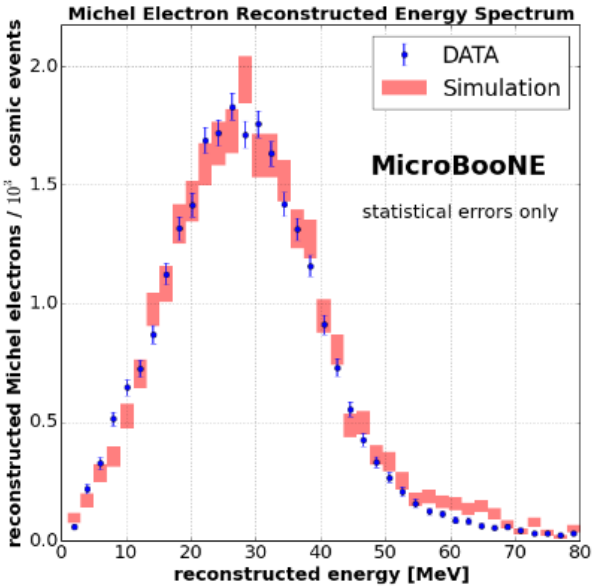
- Low-Level TPC Calibrations/Reconstruction
- Photodetector Calibrations/Reconstruction
- Particle/Event Reconstruction
- **Calibration Sources**
- High-Level Calibration/Reconstruction
- Needs for SBN and DUNE



Stopping Tracks, Michels

J. Raaf, D. Caratelli

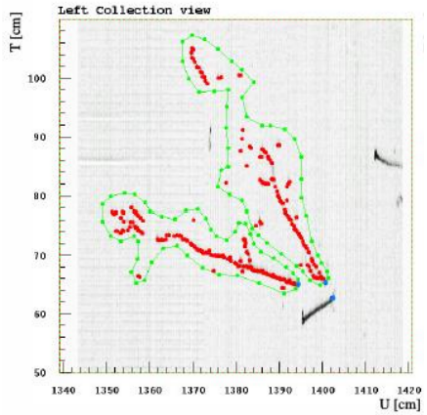


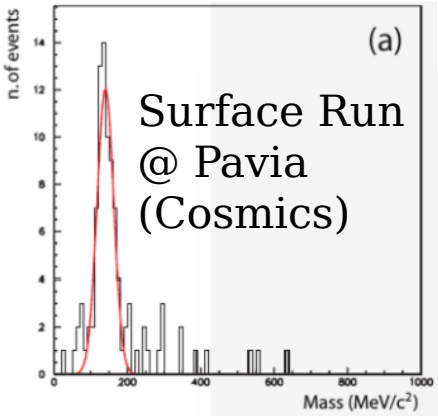


- Stopping tracks at LArIAT: beamline instrumentation provides particle ID and momentum → compare to TPC data
  - Complementarity with ProtoDUNE run in beam?
- Michel electron sample at MicroBooNE: test of charge clustering capability/limitations (radiative charge loss)
  - Clustering hard due to cosmic activity – easier underground?

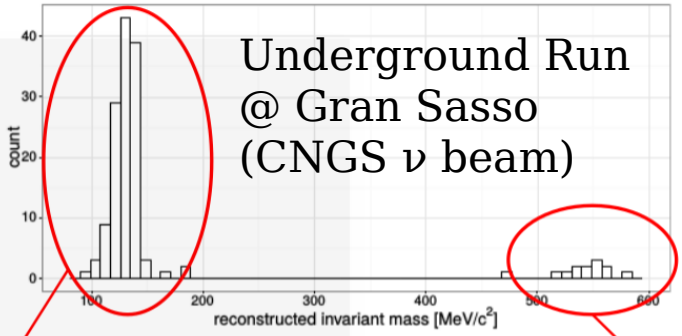
Neutral Pions @ ICARUS

A. Menegolli





Surface Run
@ Pavia
(Cosmics)

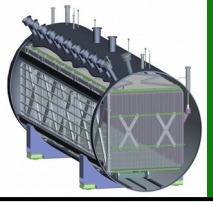


Underground Run
@ Gran Sasso
(CNGS ν beam)

- ✓ $m_{\gamma\gamma}$ = (134.5 ± 1.5 [stat] ± 4.2 [syst])MeV/c²
- ✓ π^0 mass res. ≈ 9.5% (RMS = 12.8 ± 0.8 MeV/c²)

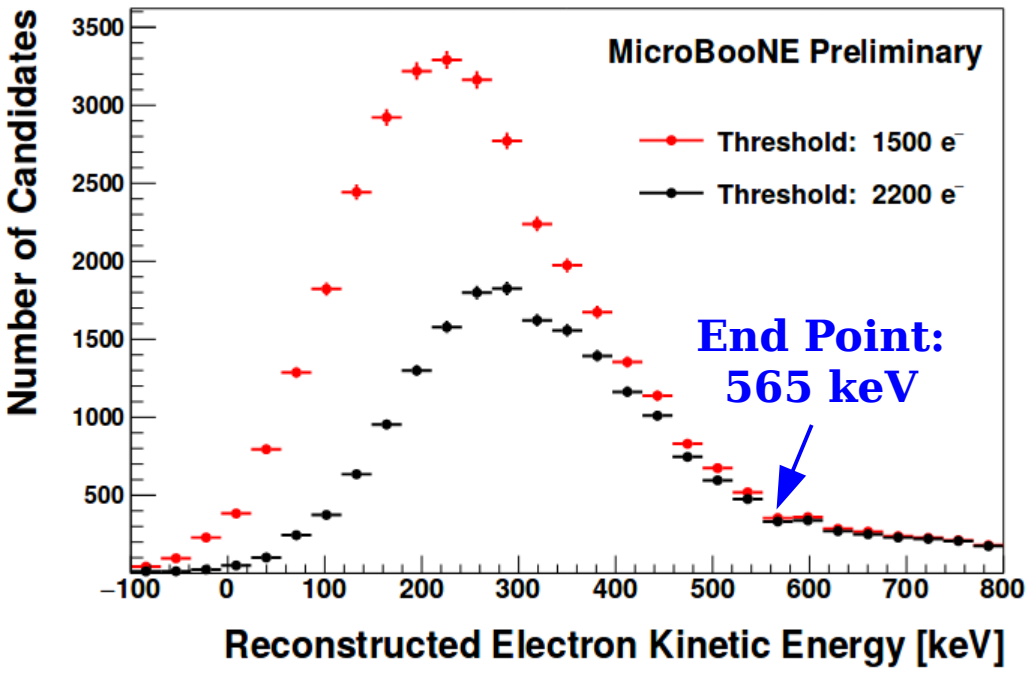
- ✓ $m_{\gamma\gamma}$ = (558 ± 23) MeV/c²
- ✓ 13 events of $\eta^0 \rightarrow \gamma\gamma$!

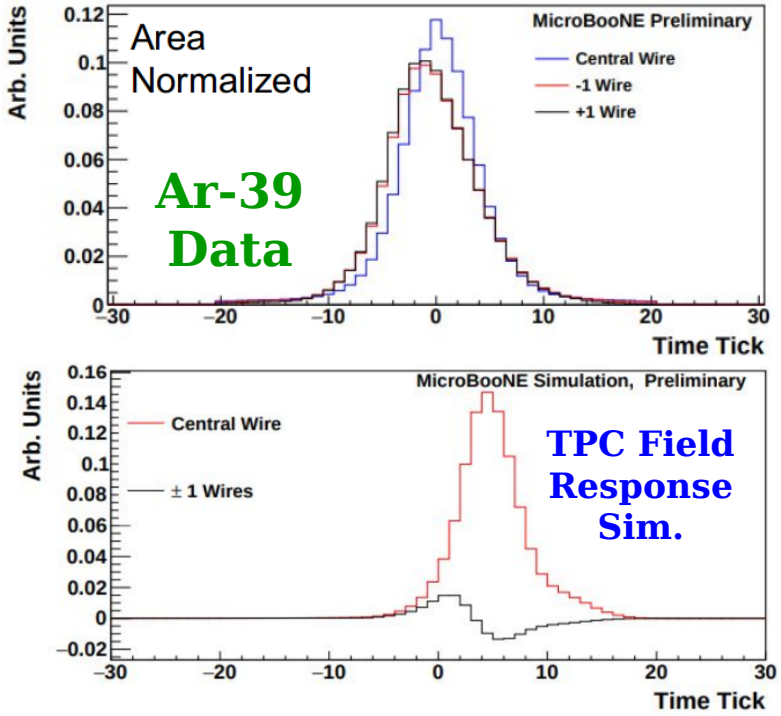
- Studies of π^0 mass reconstruction at earlier ICARUS runs
  - Both cosmic (surface) and neutrino (underground) measurements made
  - No automated reconstruction (π^0 selection/reco. “by hand”)
- Useful as benchmark for LArTPC capabilities, but need to (1) use automated reco. and (2) study larger sample



^{39}Ar Beta Decays

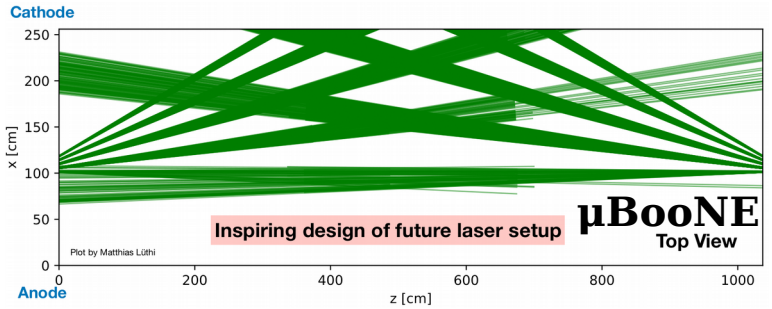
H. Rogers

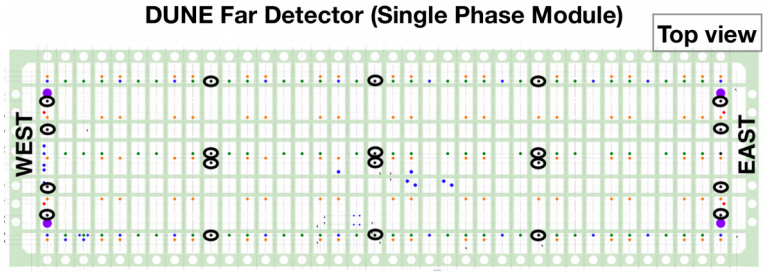




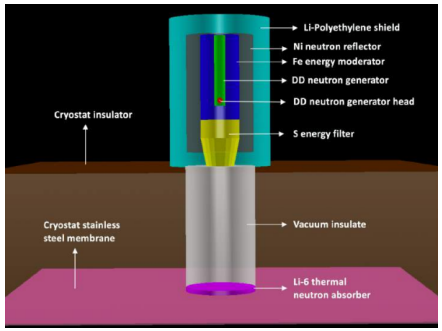
- First reconstruction of ^{39}Ar beta decays in a large LArTPC
- Relevant for reconstruction of low-energy solar/supernova neutrinos in large LArTPCs (e.g. DUNE)
- Useful for monitoring (electric field distortions, wire-to-wire response) and calibrations (electron lifetime, diffusion)

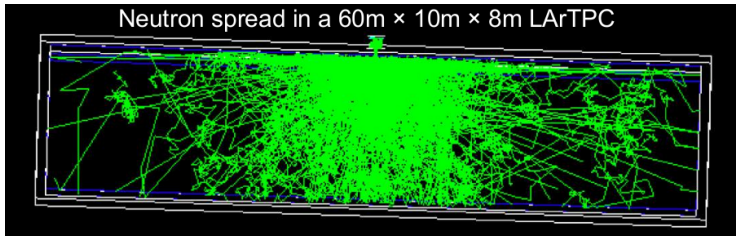
External Calibration Sources



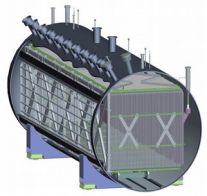


Y. Chen, J. Wang





- Two external calibration sources being considered for use at DUNE far detector:
  - <u>UV laser system</u>: target electric field distortions (space charge will be small, but hardware-related?); also **SBND**
  - <u>Pulsed D-D neutron source</u>: use neutron-argon anti-resonance to permeate deep into detector; use resultant photons for energy scale calibrations
- Deployable radiological sources also being considered



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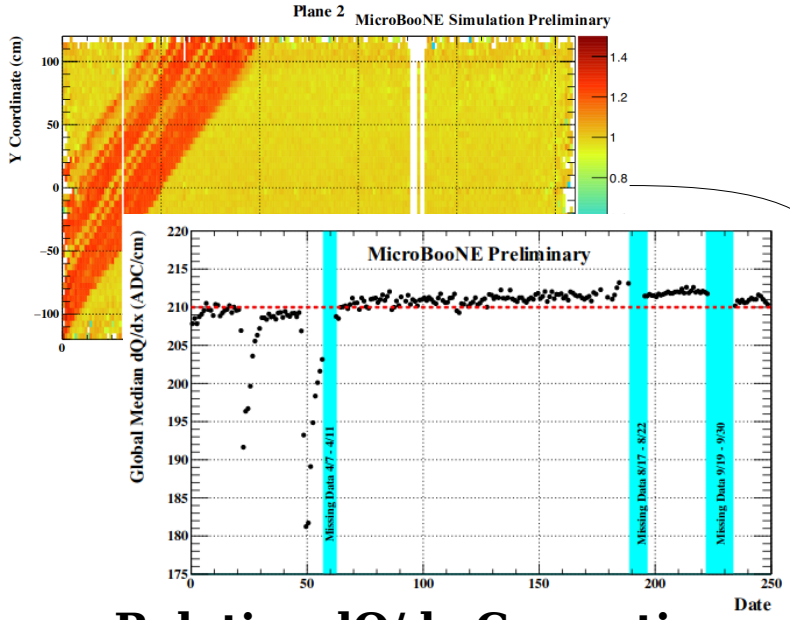
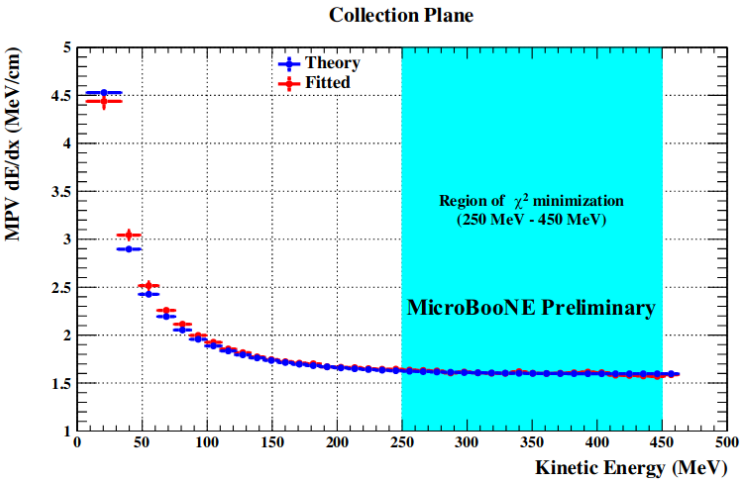
dQ/dx Uniformity, dE/dx

V. Meddage

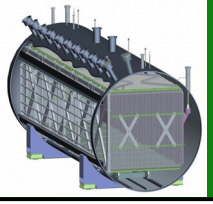


Relative dQ/dx Corrections



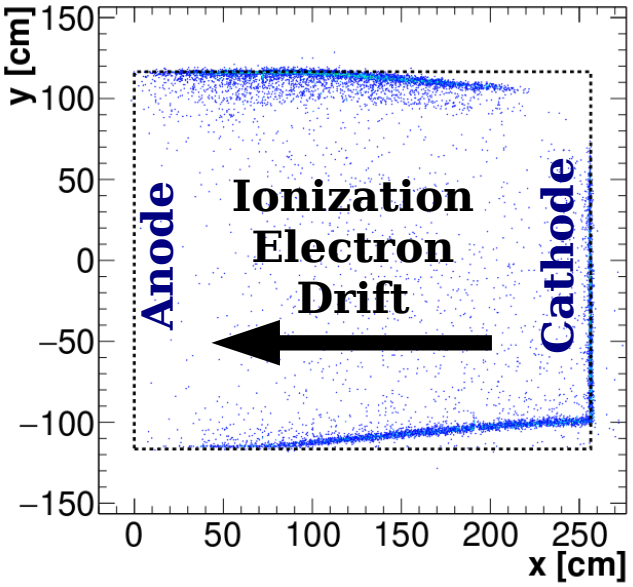
Absolute dE/dx Calibration

- Technique developed at MicroBooNE to calibrate out dQ/dx variations throughout detector (and in time)
  - Use sample of through-going anode-cathode crossing muons
- Then, impose dE/dx scale factor (scale data to agree w/ MC)
- "All-in-one" calibration; should also try detector-effect-specific calibrations (with this as cross-check/validation)



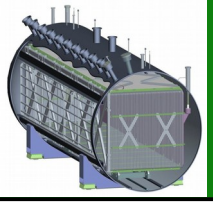
Space Charge Effects @ μBooNE

M. Mooney



Experiment	E Field	Drift Length	Max E Field Distortion	Max Spatial Distortion
MicroBooNE	273 V/cm	2.5 m	~15%	~15 cm
SBND	500 V/cm	2.0 m	~5%	~5 cm
ICARUS	500 V/cm	1.5 m	~2%	~2 cm
ProtoDUNE-SP	500 V/cm	3.6 m	~15%	~20 cm

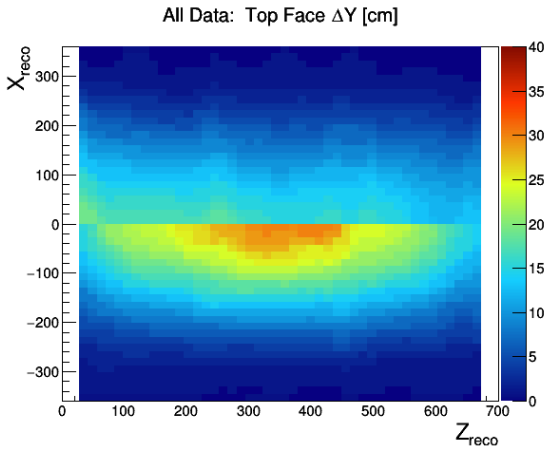
- Looking at MicroBooNE cosmic data, noticed offsets in track start/end points from top/bottom of TPC
  - Space charge effects (SCE) as **expected** (near-surface detector)
  - **Space charge**: build-up of slow-moving Ar^+ ions due to e.g. cosmic muons impinging active volume of TPC (via ionization)
  - Leads to E field distortions, distortions in ionization position
  - Calibrate out with UV laser system, crossing cosmic tracks

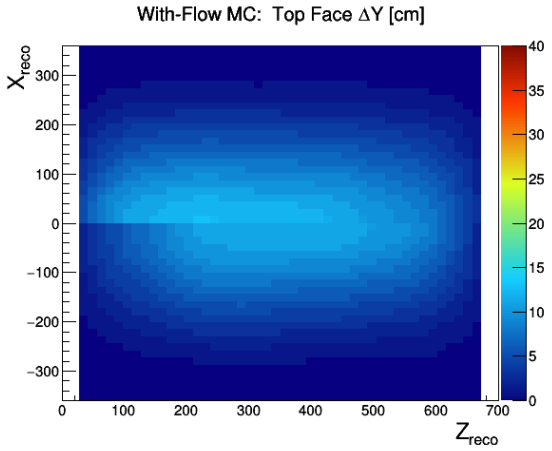


SCE @ ProtoDUNE-SP

M. Mooney

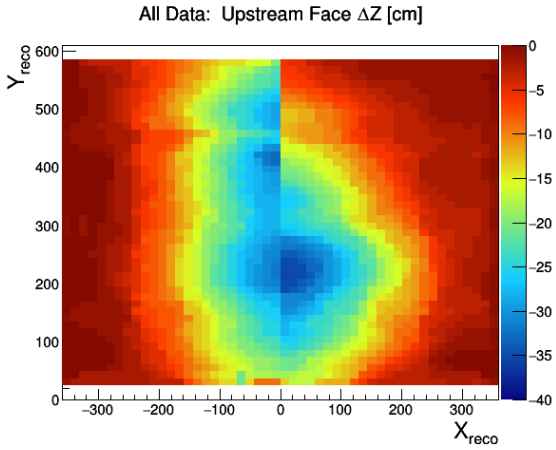
Data:
TPC Top

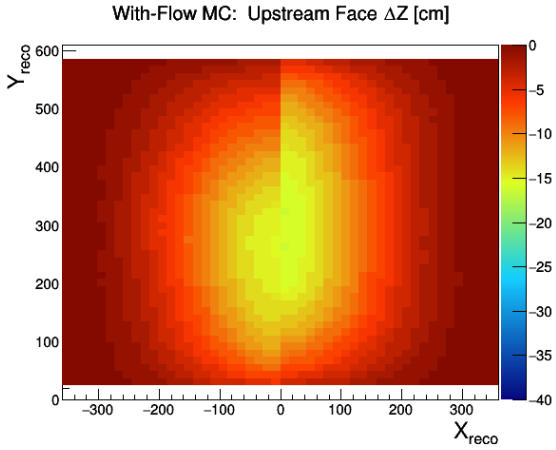




MC:
TPC Top

Data:
TPC Front



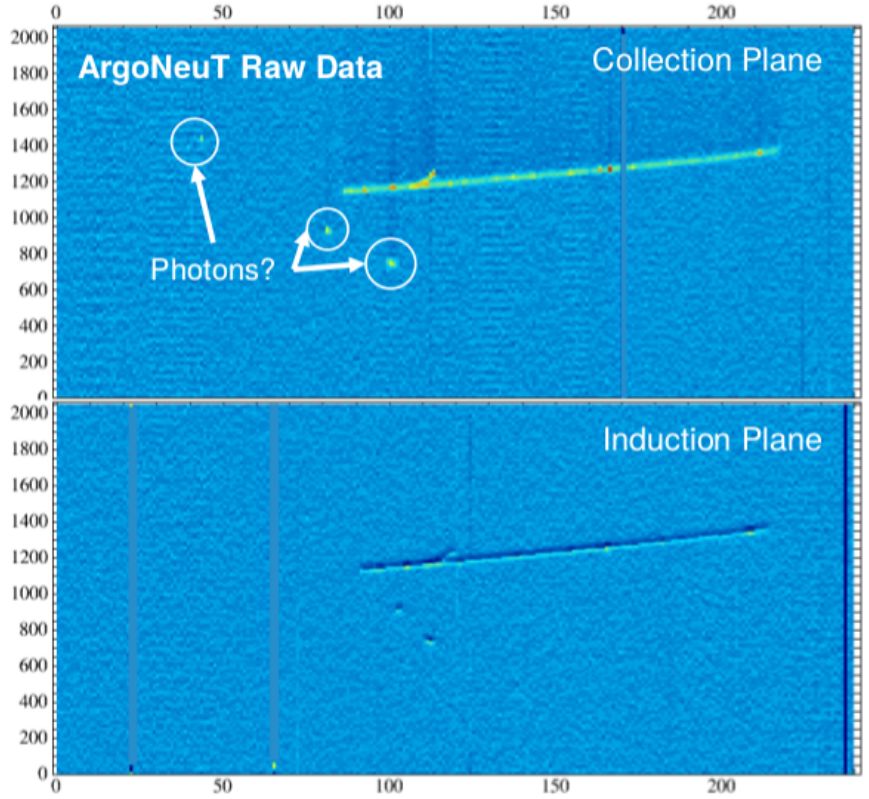


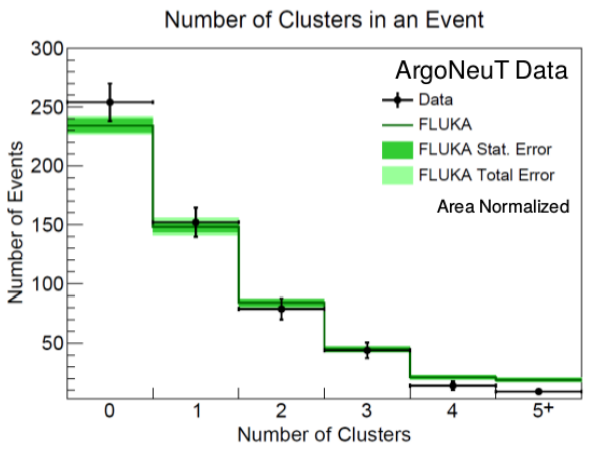
MC:
TPC Front

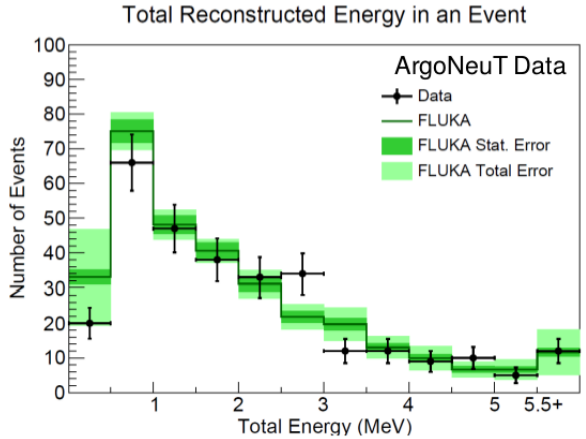
- Look at spatial offsets from top, front edges of TPC
- SCE **~50% larger** than prediction at ProtoDUNE-SP
  - Still investigating – need to tune argon flow model?

Low-Energy Photons

I. Lepetic



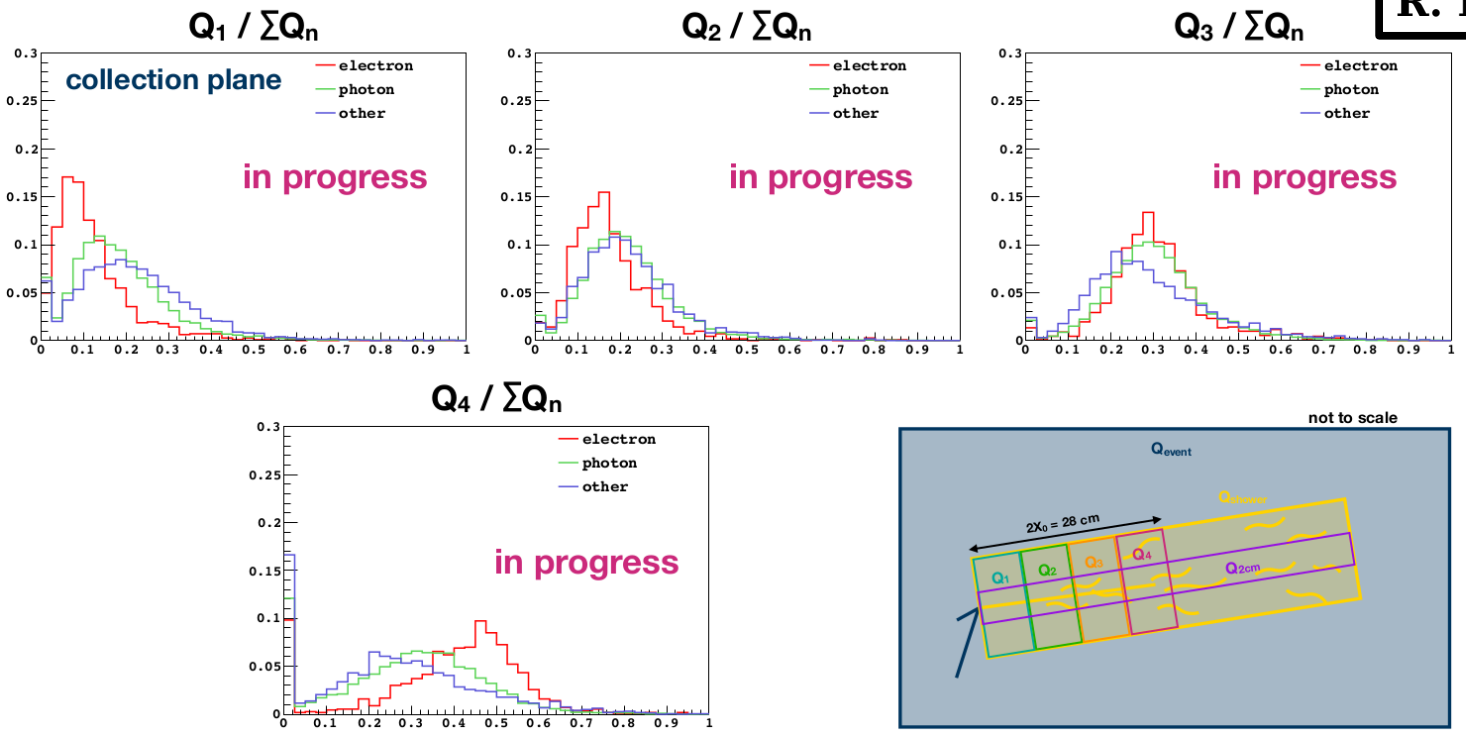




- ArgoNeuT doing physics at the MeV scale: reco. of low-energy (< 10 MeV) photons (e.g. nuclear de-excitation)
- Test of low thresholds, nuclear de-excitation models

Electron/Photon ID

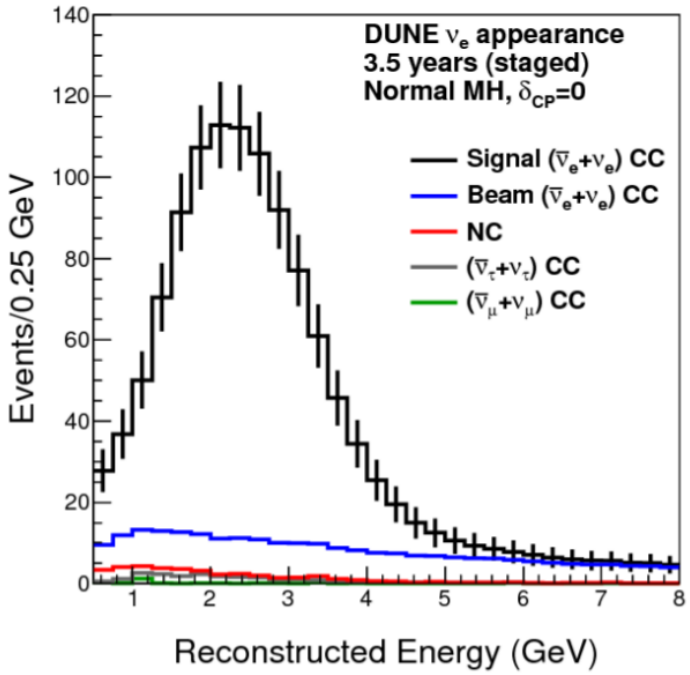
R. Fitzpatrick

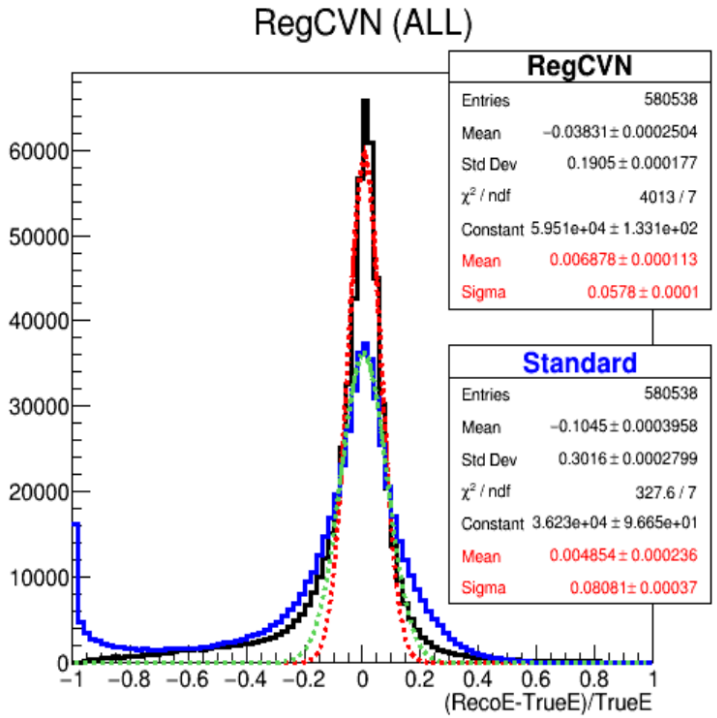


- dE/dx and spatial "gap" help differentiate electrons and photons, but in principle **can use entire shower profile**
- ArgoNeuT study looking at e/γ separation this way
  - Ideally use likelihood template of profile, like NOνA (ArgoNeuT limited in statistics, size)

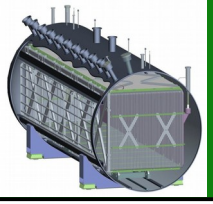
Neutrino Energy Reco.

J. Bian



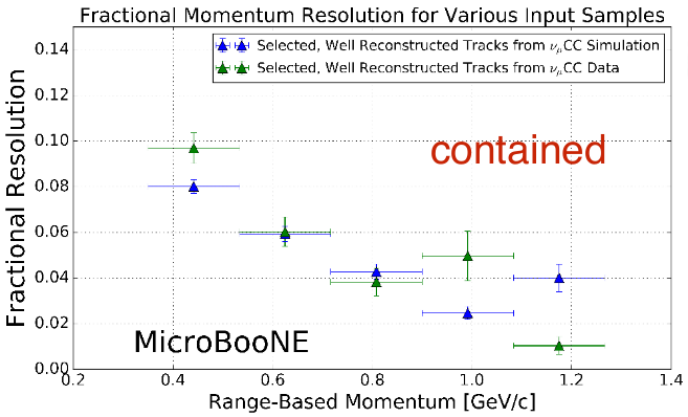


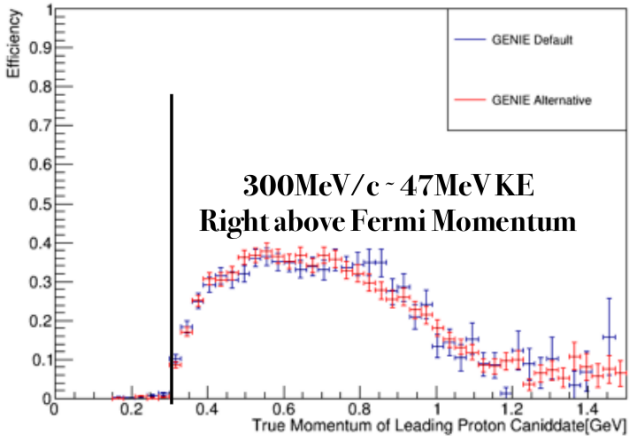
- Attempts to improve neutrino energy reconstruction at DUNE with Deep Learning techniques (regression CNN)
- Using central Gaussian width as metric, ν_e CC energy resolution improves from ~8% to **~6%** → promising!



… And Much, Much More!

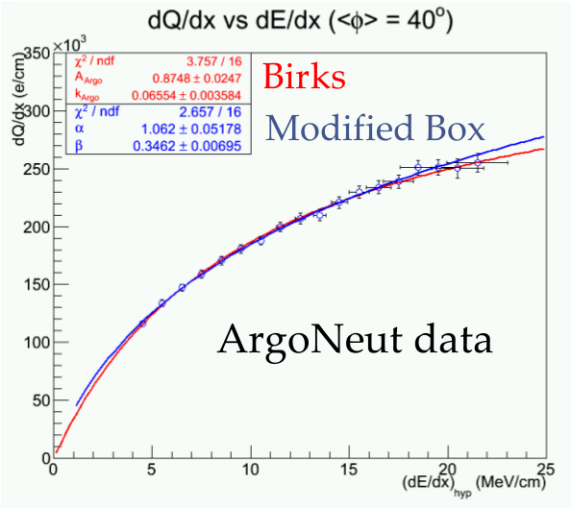
G. Cerati

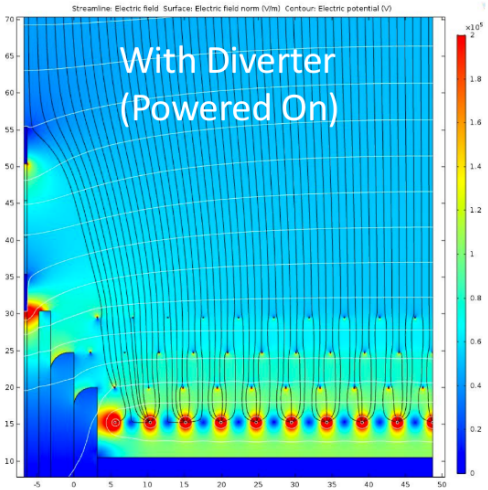




R. Castillo Fernandez

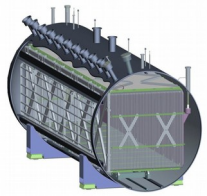
B. Baller





T. Junk

- Other contributions that I didn't have time to discuss above – please check out workshop slides online!



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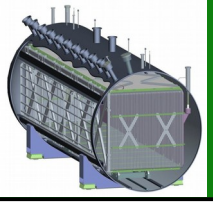
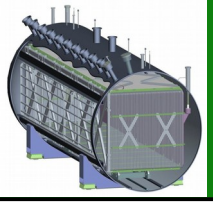


Needs for DUNE (and SBN)

K. Mahn

- Wrapped up first day of talks with presentation by Kendall Mahn (DUNE Calibration Task Force) about needs/concerns from DUNE perspective
  - Similarly interfacing with SBN calibration groups
- Challenges of DUNE:
  - Lack of cosmics! Not enough for precise, regular calibrations
- Challenges of SBN:
  - Presence of cosmics! Large cosmogenic backgrounds
- Challenges of both DUNE and SBN:
  - Need for precision calibrations and careful reconstruction to measure energies precisely and mitigate backgrounds
  - Finding a way to **work together** to make it all happen!

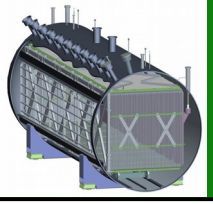


Final Remarks

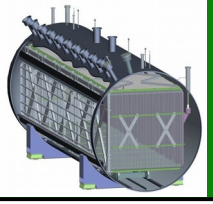
- Main feedback received from workshop attendees:
  - Be sure to communicate details of workshop to individual experiments (purpose of this talk)
  - Consider holding yearly workshops – thinking about it!
- Preparing proceedings for workshop – plan is to publish proceedings in JINST later this spring
  - Hopefully a useful resource for people to learn current state of LArTPC calibration/reconstruction
  - Useful for training new students/postdocs
- Thanks very much to:
  - The **Neutrino Physics Center** for funding the workshop
  - My tireless, amazing co-organizers, **David Caratelli** and **Tingjun Yang** (both of FNAL)

Thanks!

Workshop Indico Page: **https://indico.fnal.gov/event/18523/**



Backup

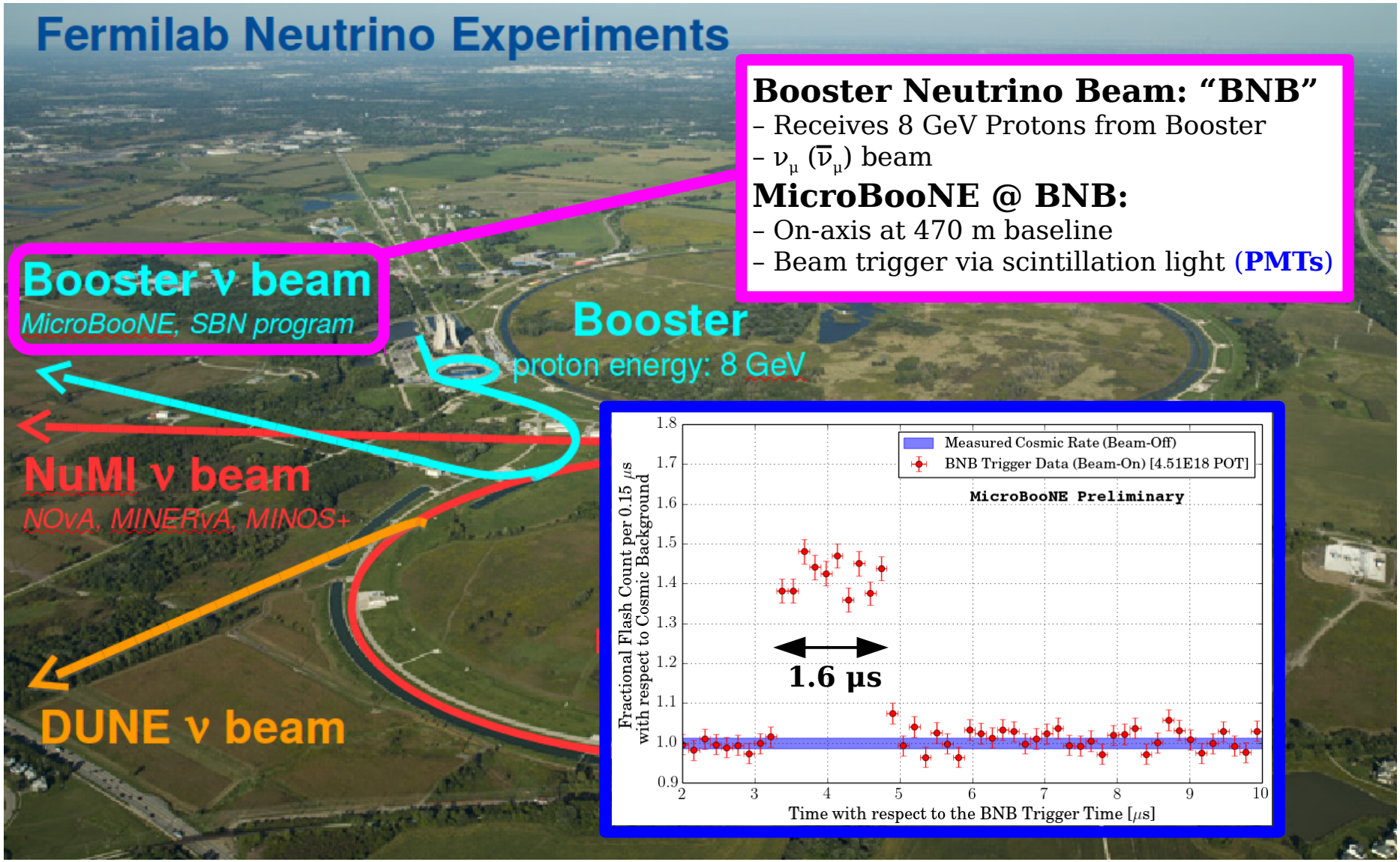


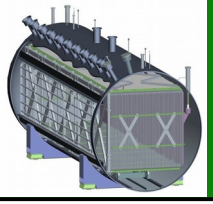
Why Liquid Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	
Approx. Cost [$/kg]	52	330	5	330	1200	

- Argon is cheap: **~1%** of atmosphere
- Dense target (more ν-N interactions per unit time)
- High scintillation light yield, argon transparent to own light
- Relatively small radiation length for shower containment

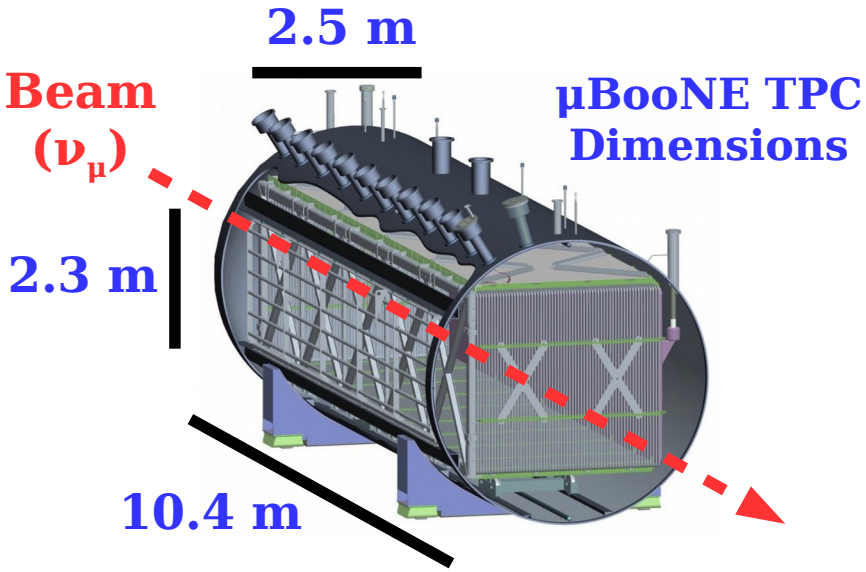
Beamlines at Fermilab

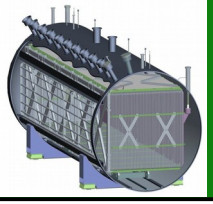




MicroBooNE Overview

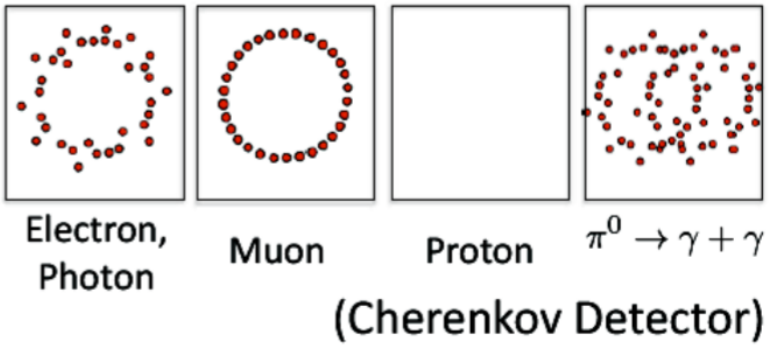
- "Micro Booster Neutrino Experiment"
  - Accelerator ν experiment @ FNAL
  - LArTPC with 85 ton active mass
  - Near-surface operation
  - **Non-evacuated liquid argon fill**
  - **Cold (in LAr) front-end electronics**
  - **UV laser calibration system**
- Physics goals:
  - **Investigate MiniBooNE low-energy excess**
  - Measure first low-energy ν-Ar cross sections
  - Key step for Short-Baseline Neutrino (SBN) program
  - R&D for Deep Underground Neutrino Experiment (DUNE)

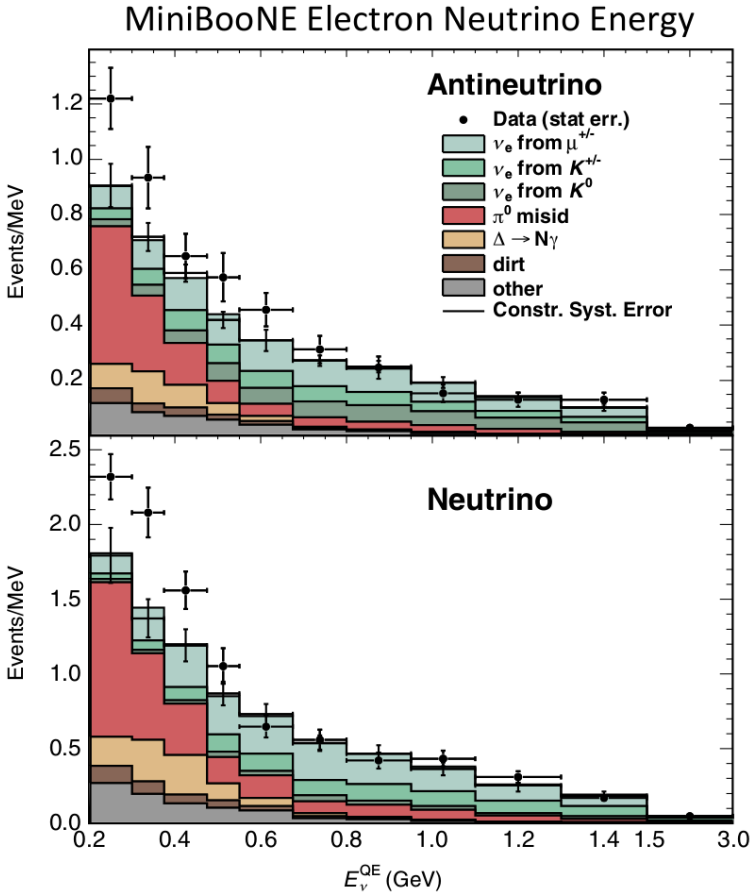


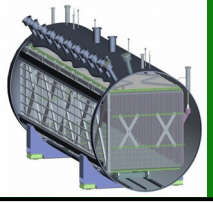


Motivation for MicroBooNE

- Low-energy ν_e / $\bar{\nu}_e$ candidate excess seen at **MiniBooNE**
  - MiniBooNE: Cherenkov detector (also on BNB)
  - Baseline too short (541 m) for 3-flavor $\nu_\mu \rightarrow \nu_e$ oscillation
- No $e^{\pm}/\gamma$ separation... is excess misunderstood background, sterile neutrino, or... ?

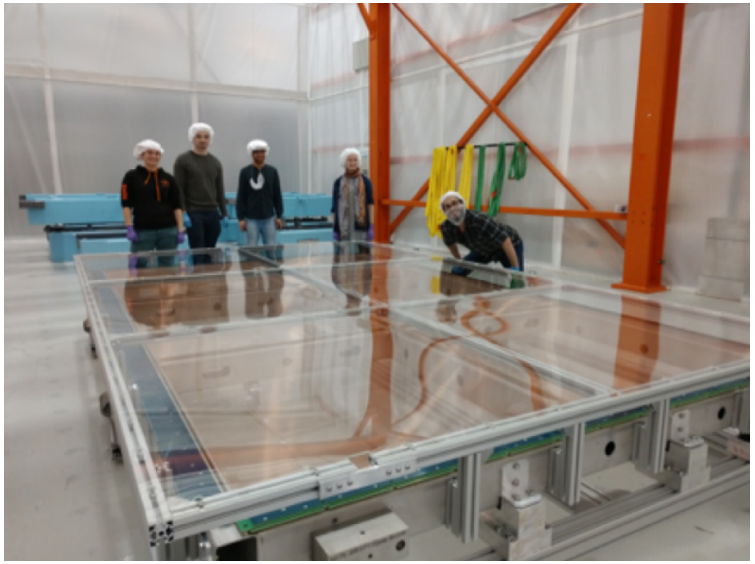






Status of SBND, ICARUS

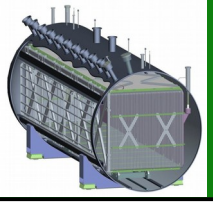
SBND Status



- First APAs at FNAL
- Electronics QC underway
- Cryostat in design phase
- Begin taking physics data in **early 2021**

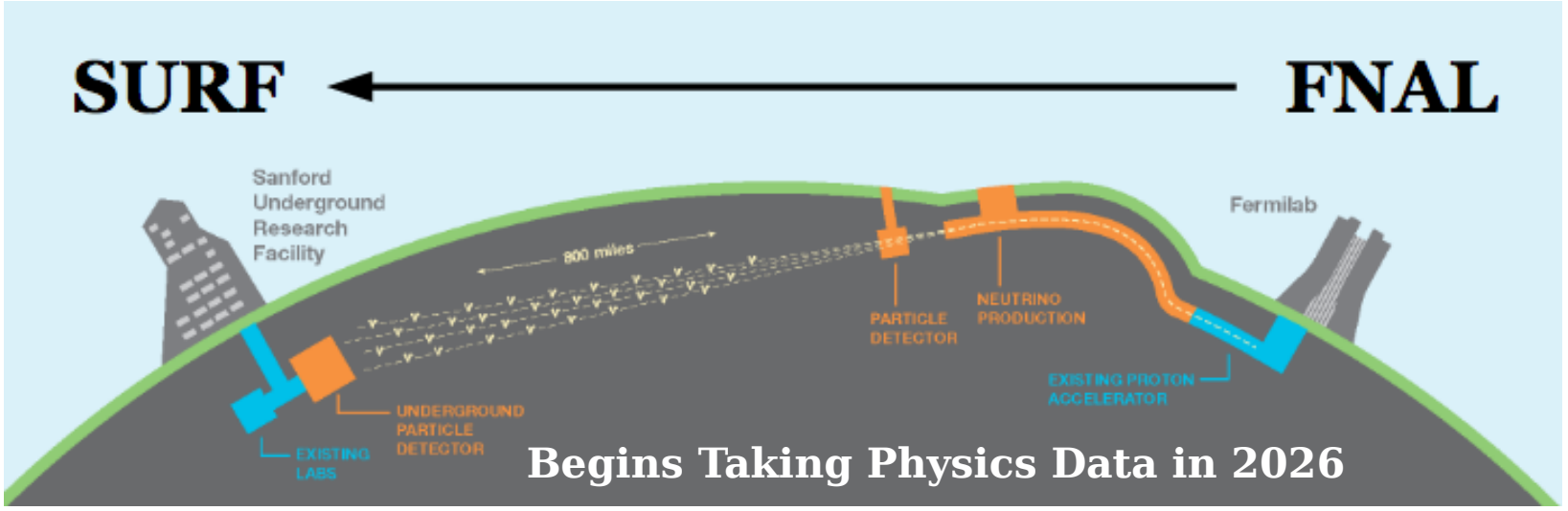
ICARUS Status

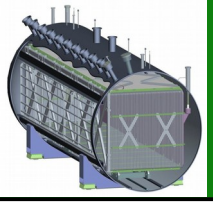
- Cold vessels (with TPCs) delivered from Italy
- Installation of electronics feedthroughs underway
- Begin taking physics data in **early 2020**



Going Big: DUNE

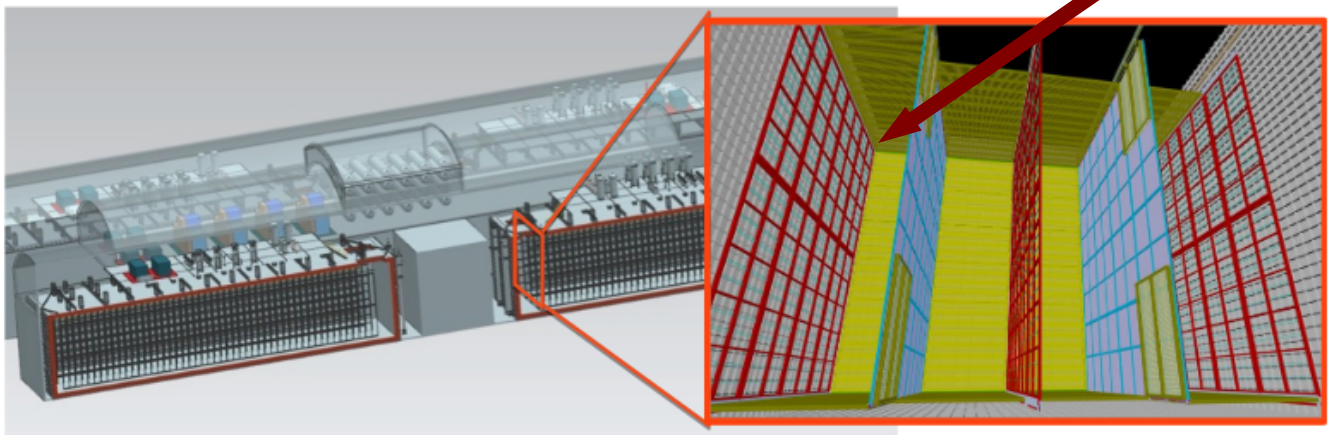
- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (40 kt) LArTPC far detector and near detector
  - Far detector 1.5 km underground
  - Wide-band, on-axis beam
- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - **Ordering of ν masses**
    - **δ_{CP}**, θ_{23}, θ_{13}
  - Nucleon decay
  - Supernova burst neutrinos
  - Solar neutrinos

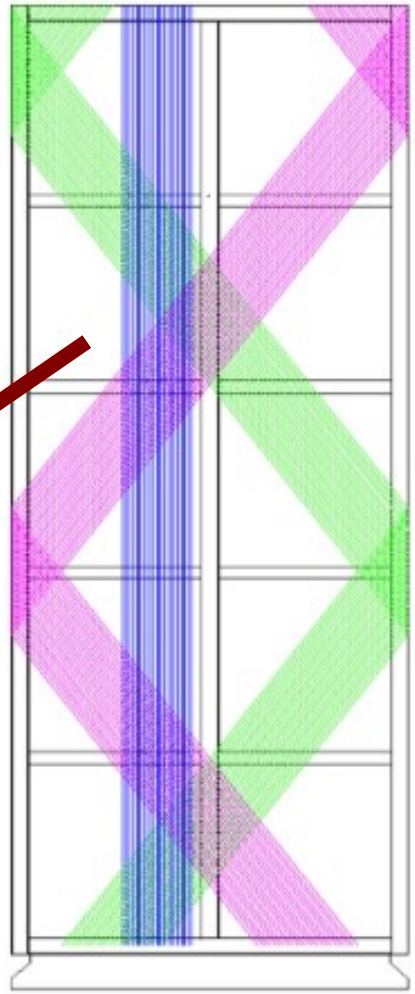




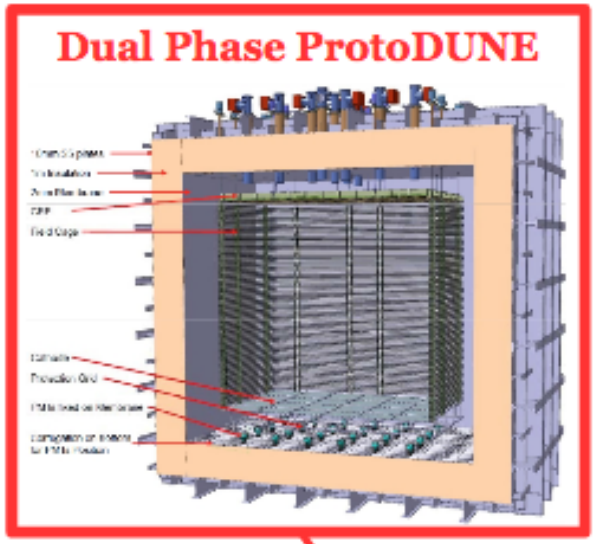
Far Detector LArTPC

- Two far detector (FD) designs being considered: single phase (LAr) and dual phase (LAr + GAr)
- Single phase FD uses modular drift cells (scalable)
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs), **3.6 m drift**
  - **Wrapped wire** to reduce number of readout channels needed and cabling complexity
- Four 10-kt modules deployed in stages

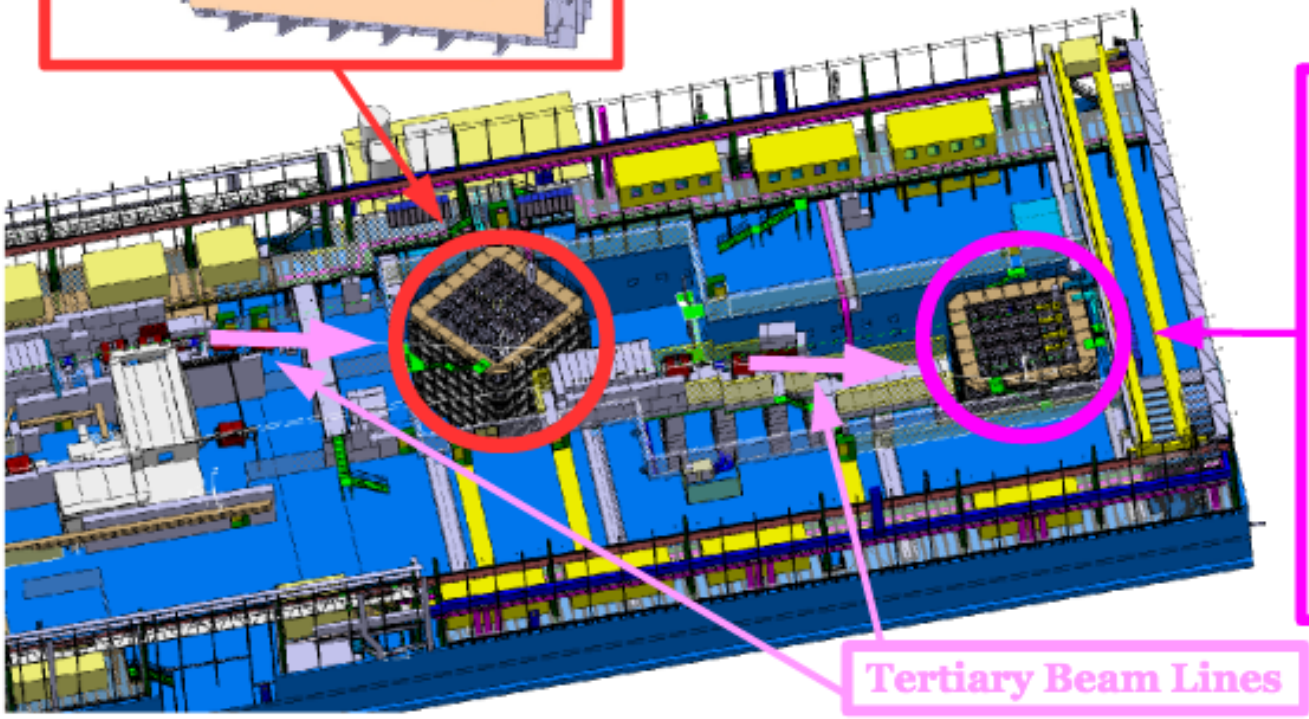


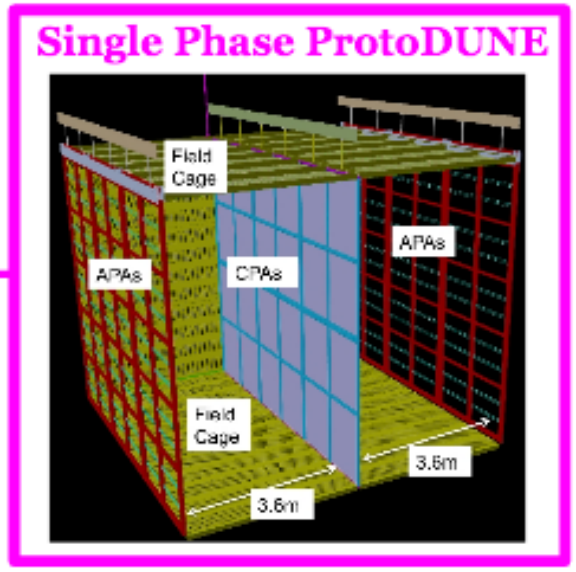


ProtoDUNEs

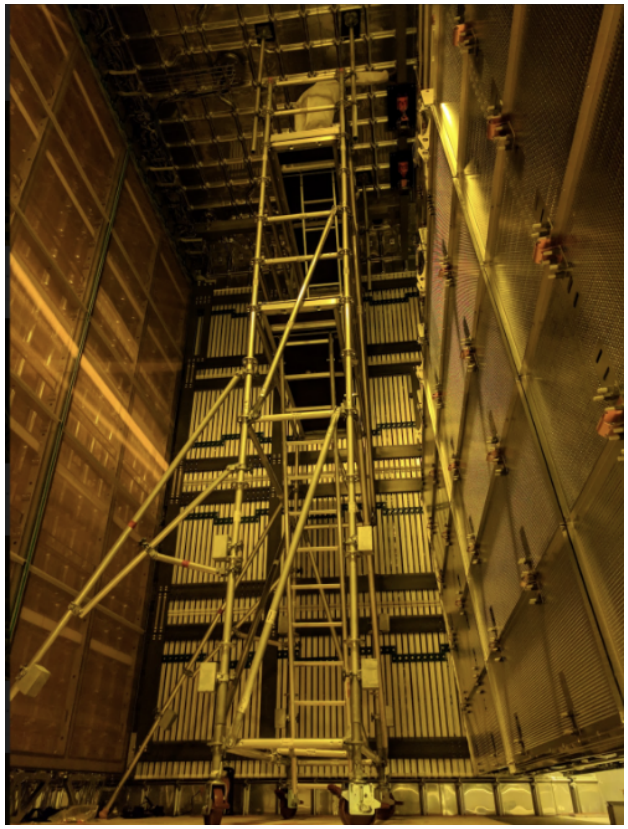


- Two ~6×6×6 m^3 "ProtoDUNEs" in test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since September 2018; ProtoDUNE-DP in 2019



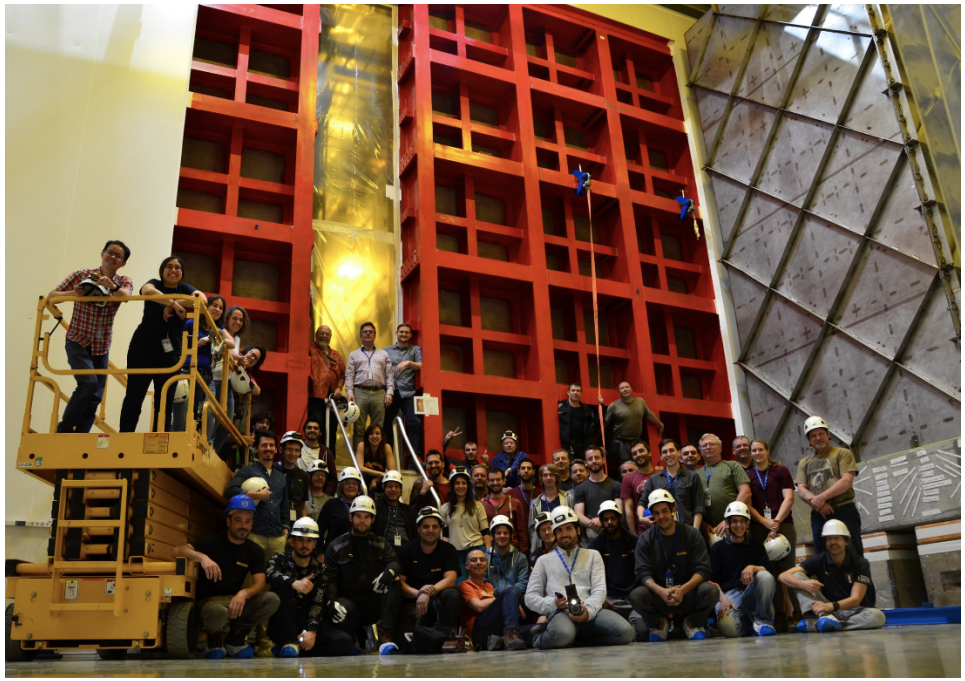


ProtoDUNEs

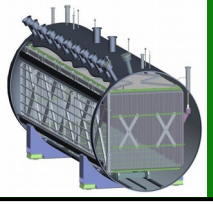


Inside ProtoDUNE-SP

- Two ~6×6×6 m^3 “ProtoDUNEs” in test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since September 2018; ProtoDUNE-DP in 2019

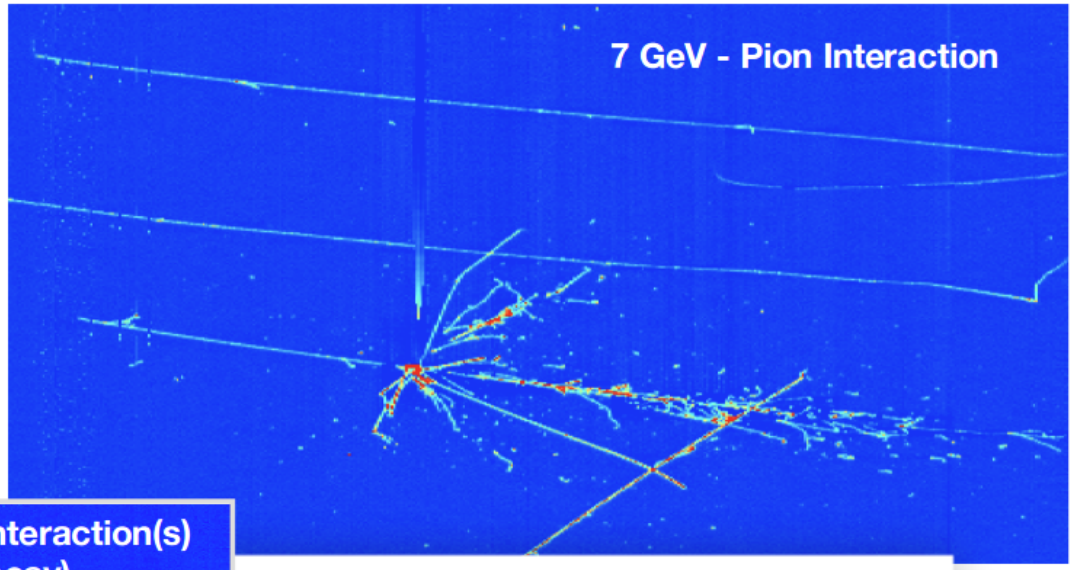


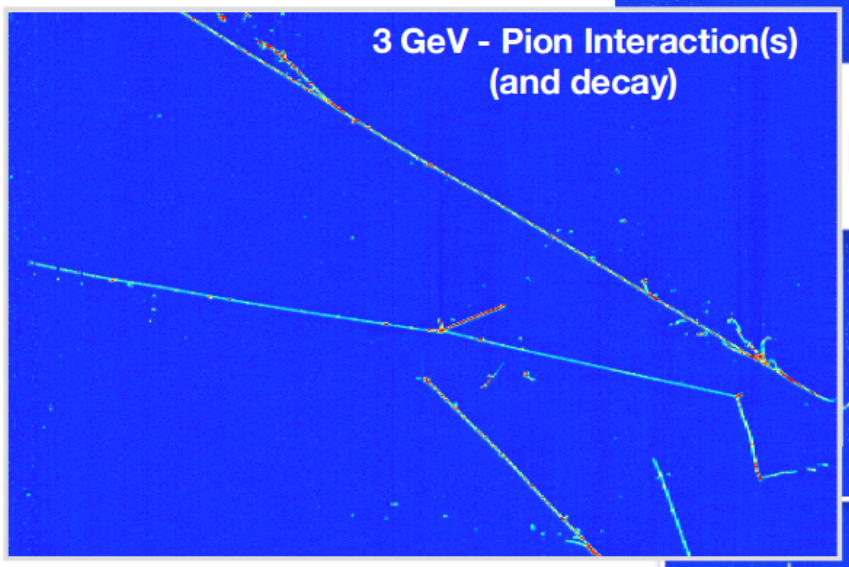
ProtoDUNE-SP Prior to Closing of Temporary Construction Opening



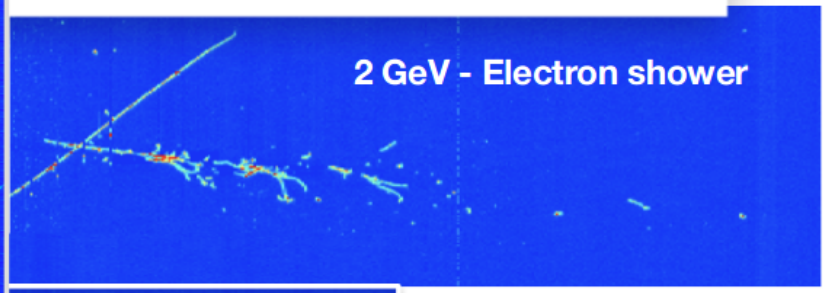
First Beam Events

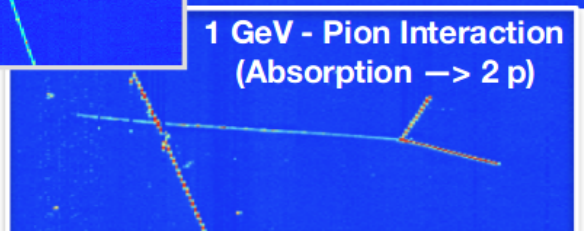
- First events in data from charged beam (μ, π, K, p, e)



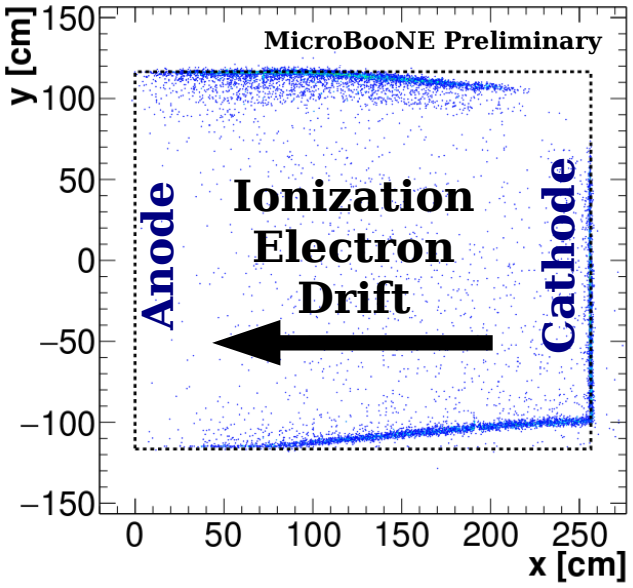


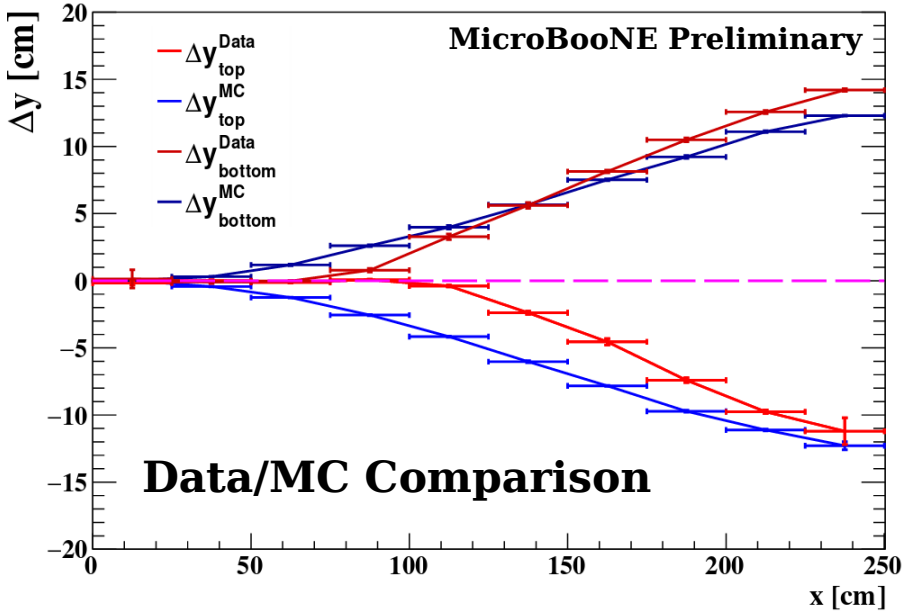
PROTO DUNE SP





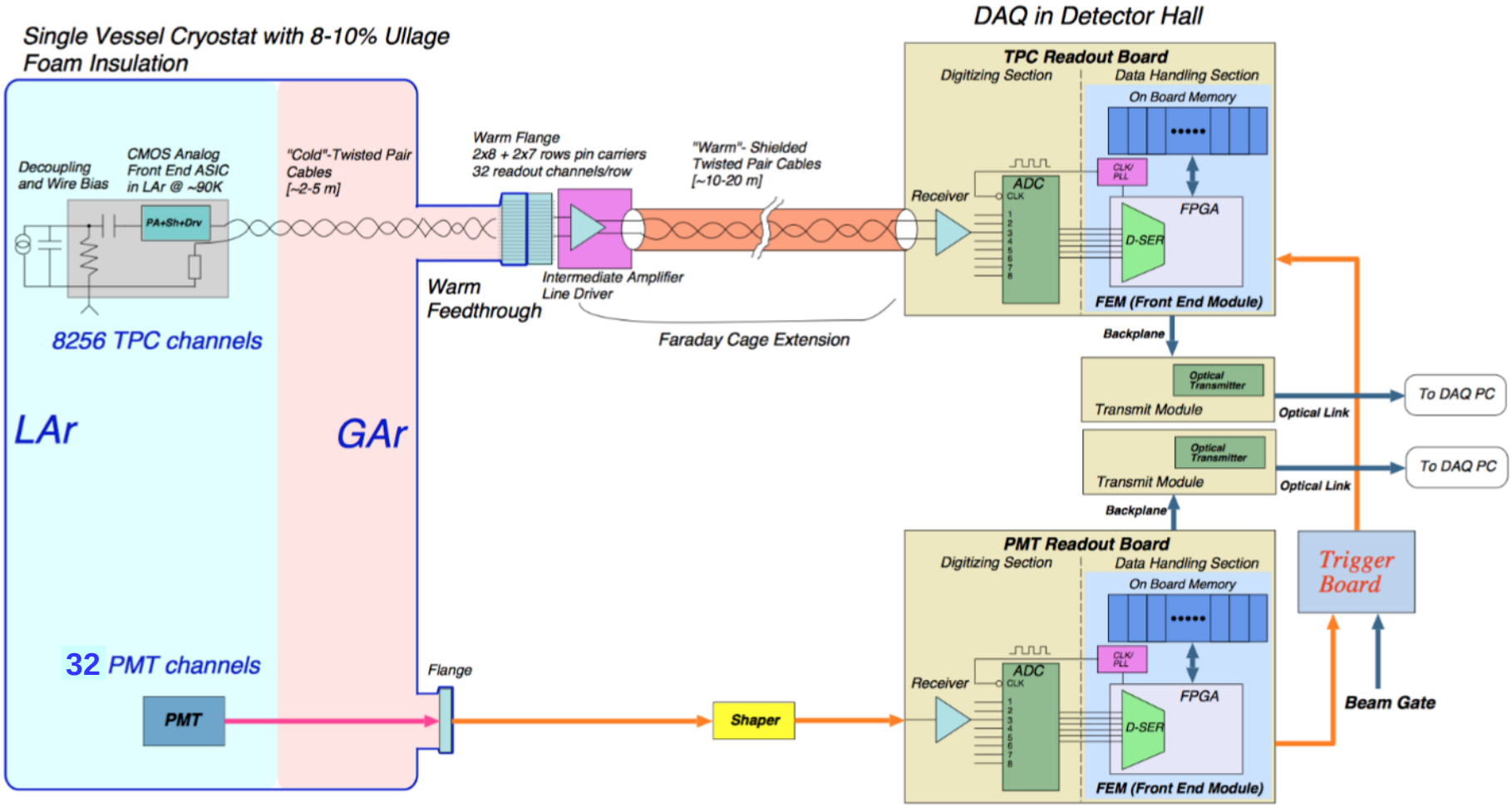
SCE Data/MC Comparison





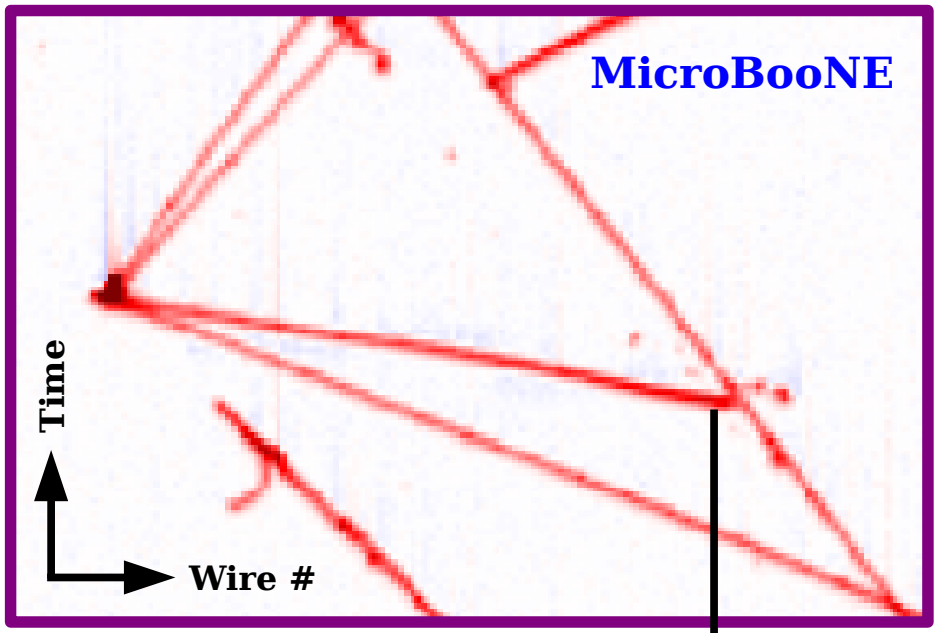
- SCE simulation qualitatively reproduces effect
  - Some differences… impact from **liquid argon flow?**
  - Can impact track/shower reconstruction and calorimetry
    - **5-10%** calorimetric bias/smearing – **worse at ProtoDUNEs**
- Calibrate **in 3D** using **UV laser system**, cosmic muon tracks

µBooNE Electronics Chain

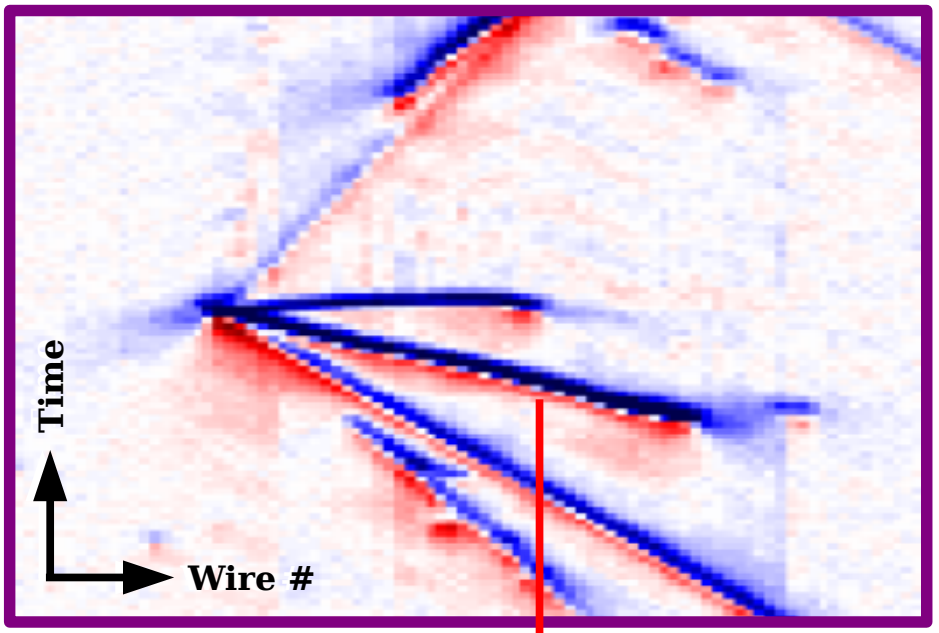


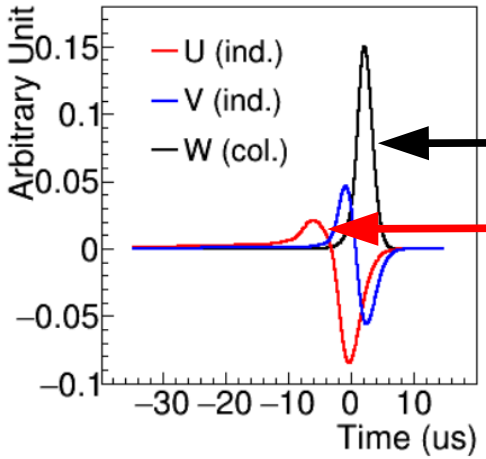
Different Plane Views

"Collection" Plane (Y)



"Induction" Plane (U, V)

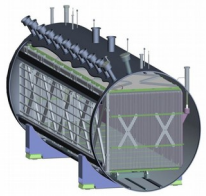




Collection Wire Response:
Unipolar Signal

Induction Wire Response:
Bipolar Signal

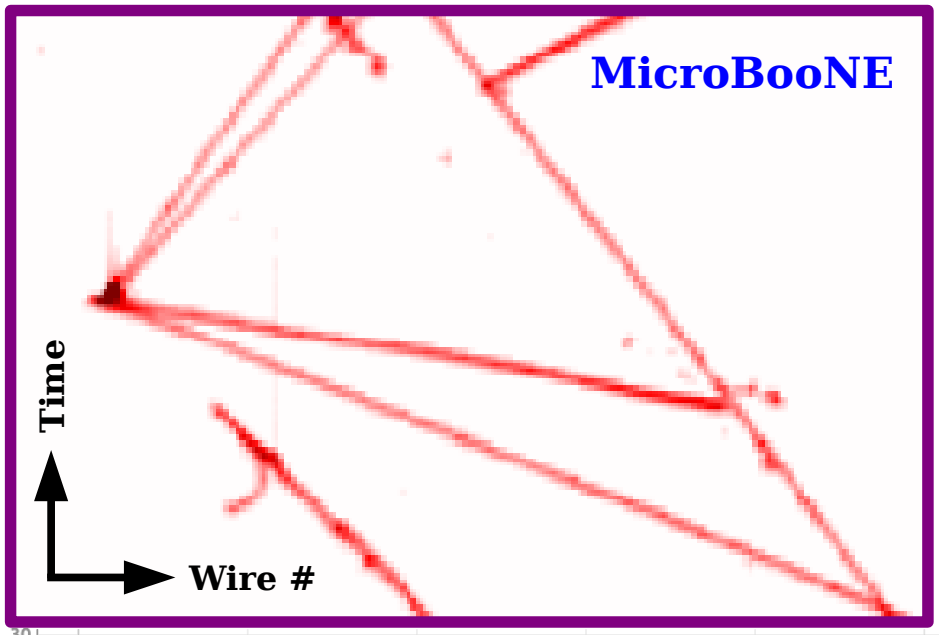
In order efficiently find ionization signal and correctly determine charge, must first *remove detector response* → **deconvolution**



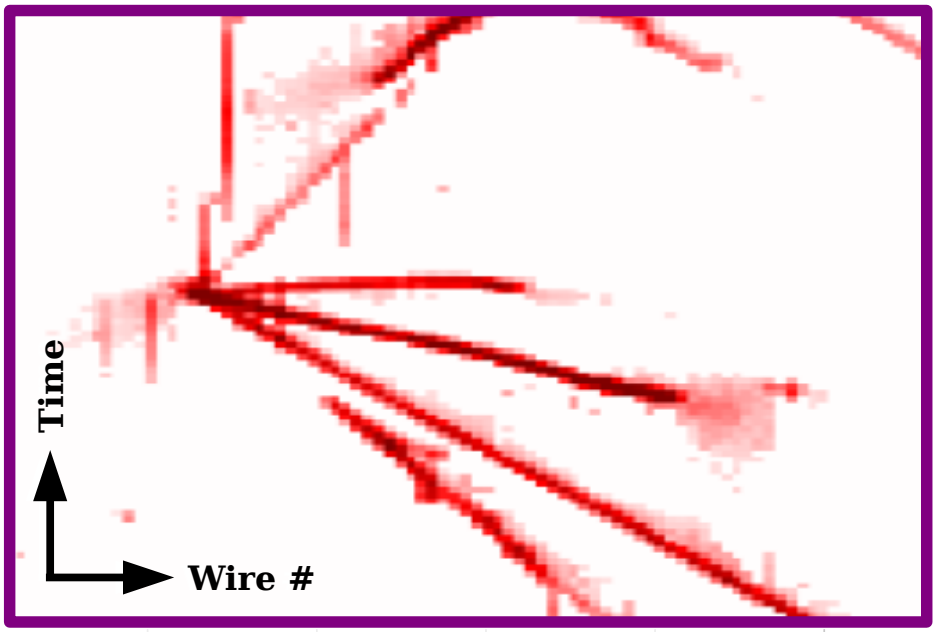
Deconvolution:

$$S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega)$$

"Collection" Plane (Y)



"Induction" Plane (U, V)

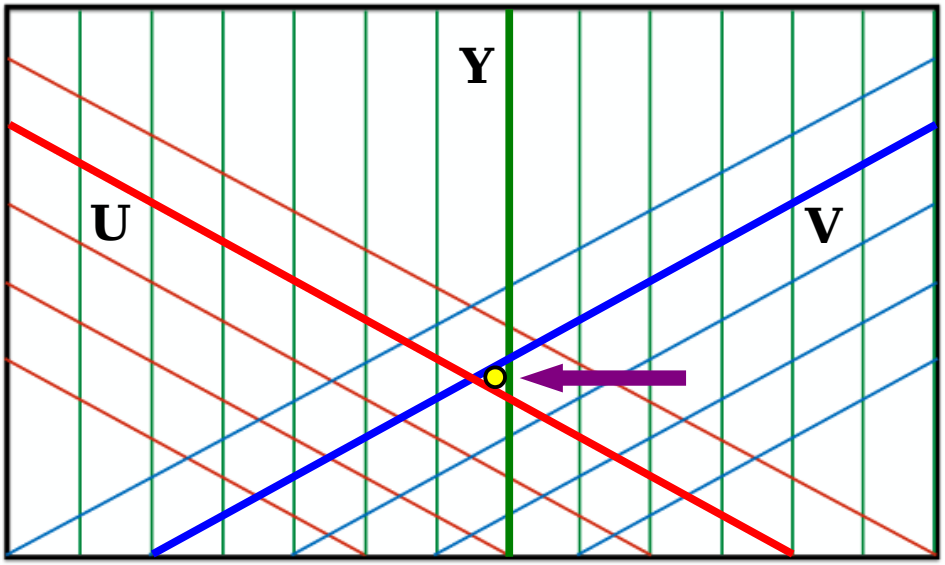


Filter (F): Prevents Blow-up of Noise During Deconvolution

ArgoNeuT Waveforms

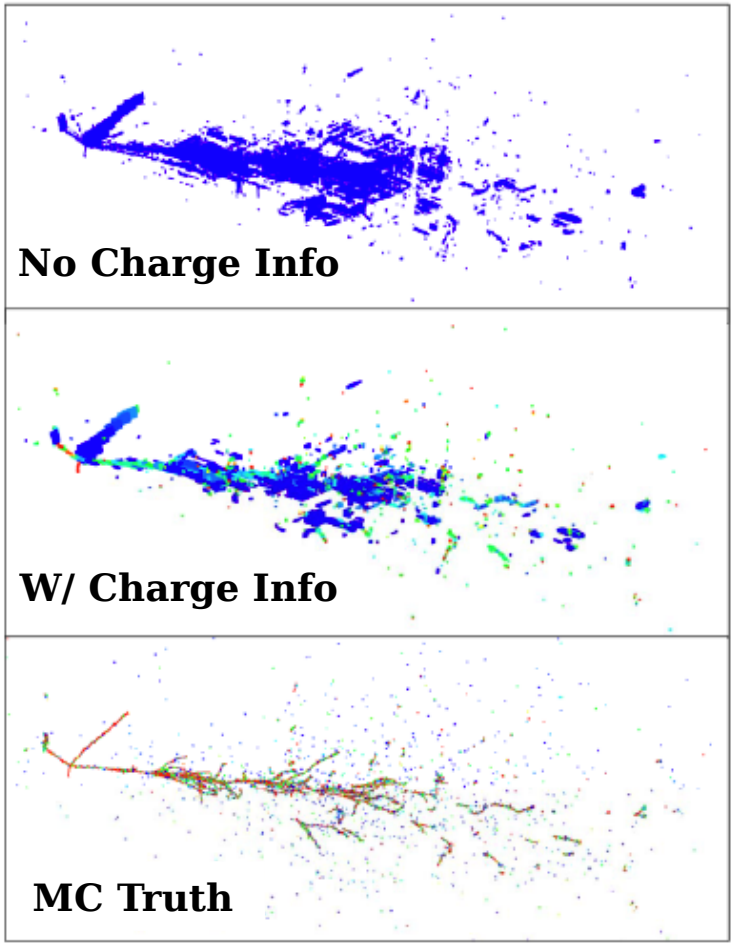
3D Event Reconstruction

- Multiple ways to get to 3D:
  - Identify clustered tracks/showers in 2D, match across planes
  - Create 3D hits from wire triplets (matching **charge**) and directly cluster tracks/showers in 3D
    - New **BNL "Wire-Cell"** method



Same Charge Seen on All Three Wires

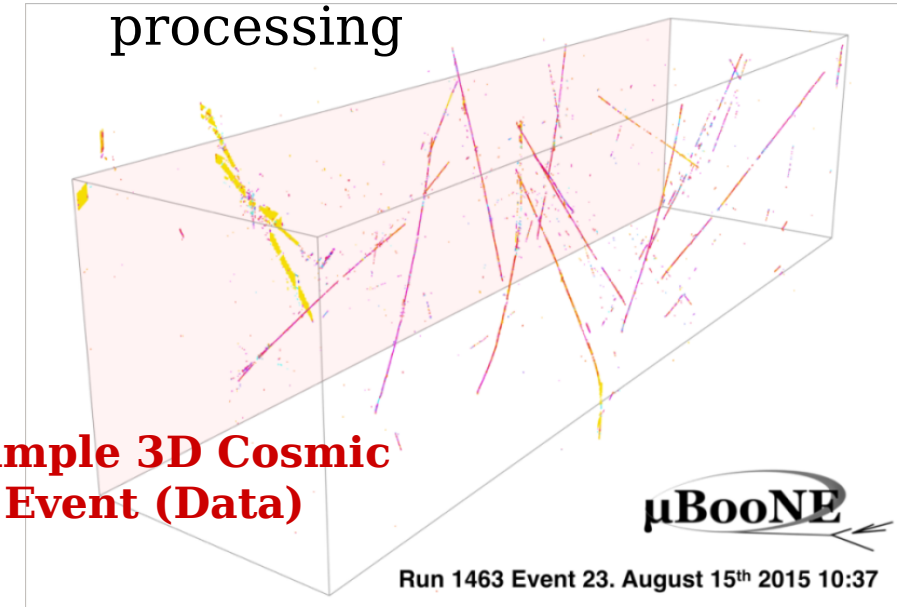
Example MC Interaction Event (2D Projection of 3D)



http://www.phy.bnl.gov/wire-cell/bee/

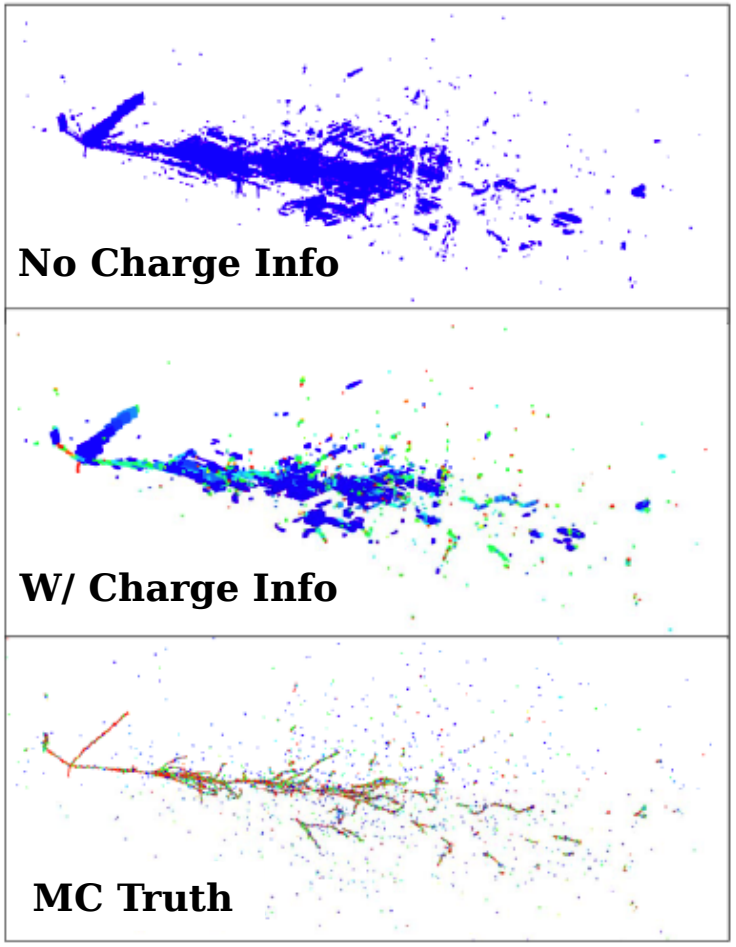
Wire-Cell: Fully Using TPC

- Wire-Cell method uses full power of TPC: charge correlations across planes for localized ionization
  - Allows for better imaging before pattern recognition
  - Requires careful signal processing



Example 3D Cosmic Event (Data)

Example MC Interaction Event (2D Projection of 3D)

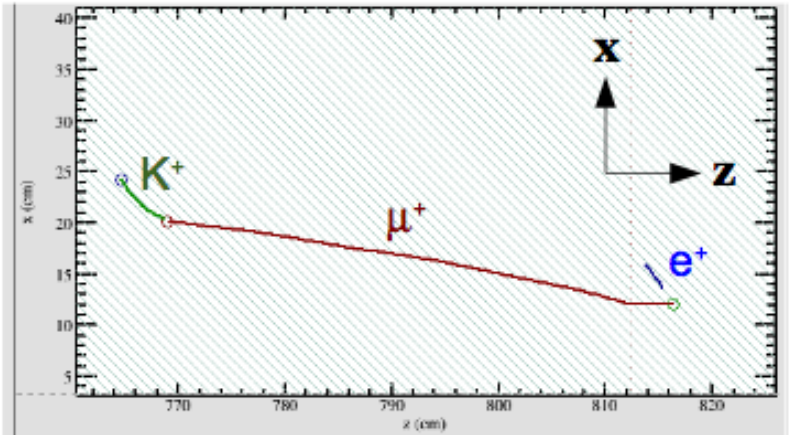


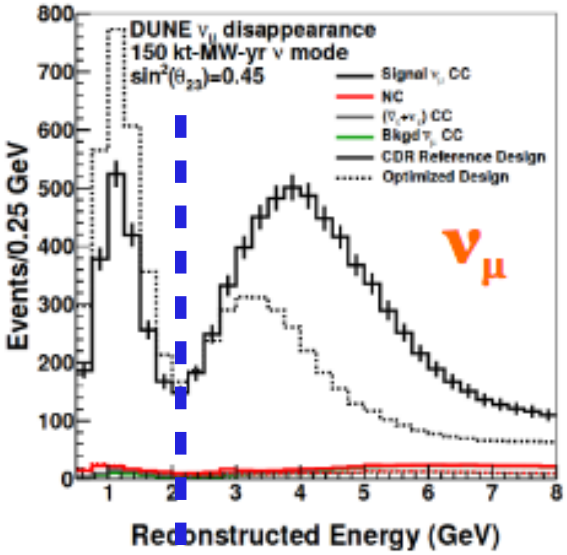
http://www.phy.bnl.gov/wire-cell/bee/

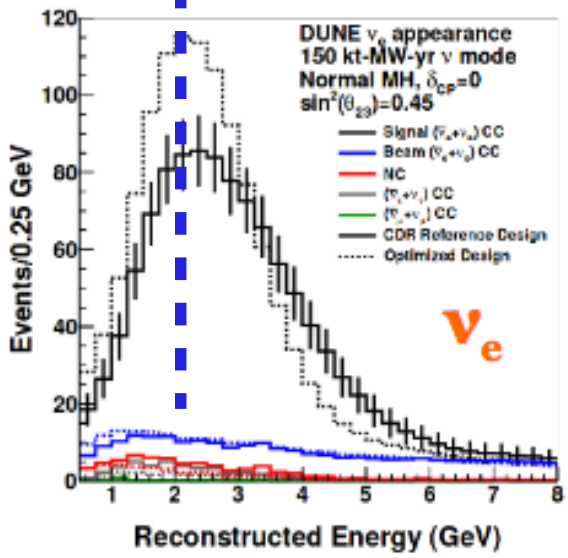
DUNE Physics Goals

- LArTPC provides high signal efficiency, low backgrounds for **oscillation physics**
  - Extract ν oscillation parameters by means of a 4-sample (ν_μ / $\overline{\nu}_\mu$ / ν_e / $\overline{\nu}_e$) fit
- Also will excel at detecting **proton decay** modes with kaons in final state
  - Large detector, underground, fine spatial granularity (low background)

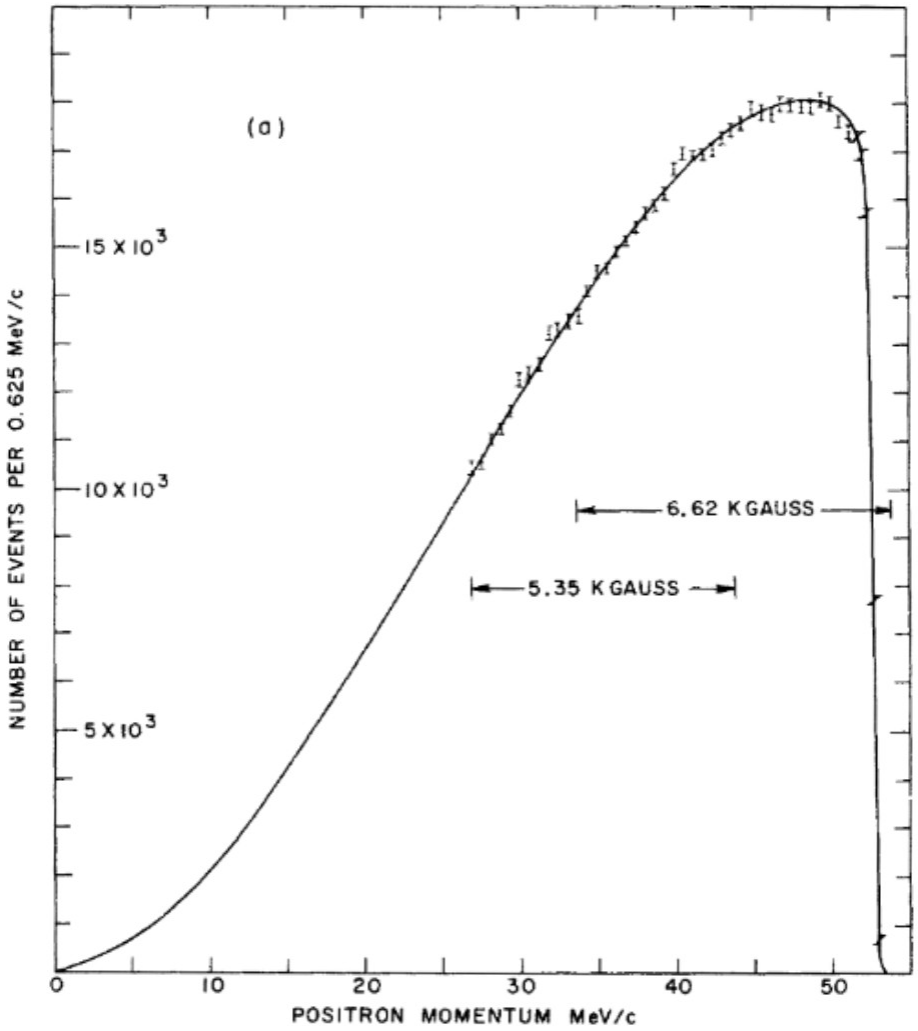
Simulated $p \rightarrow \overline{\nu} K^+$ event:



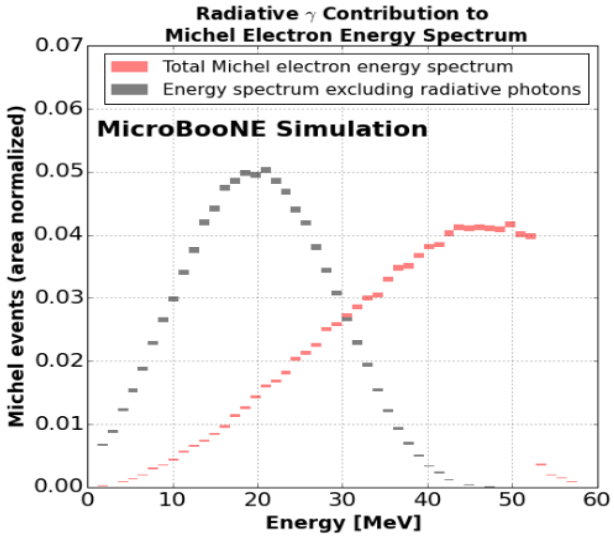


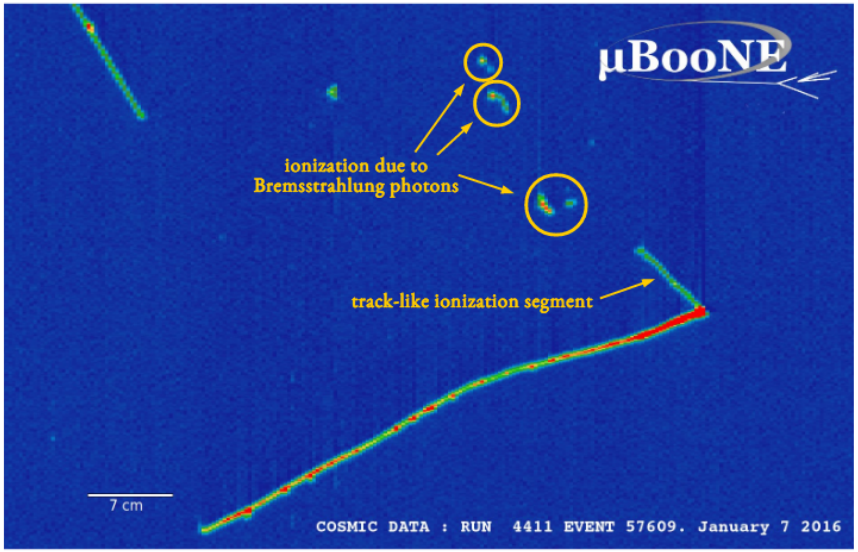


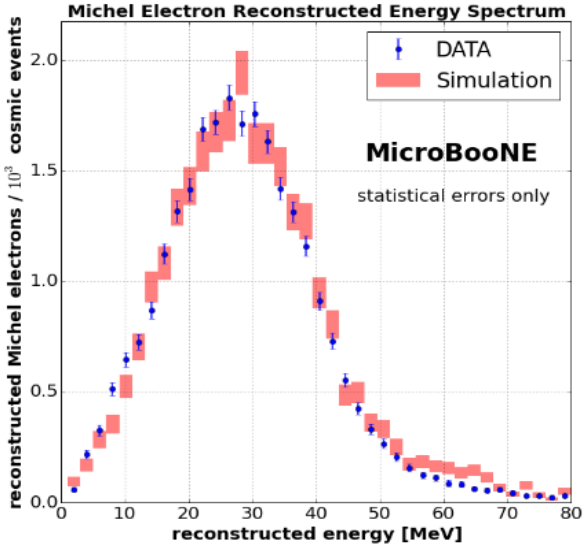
True Michel e^- Spectrum

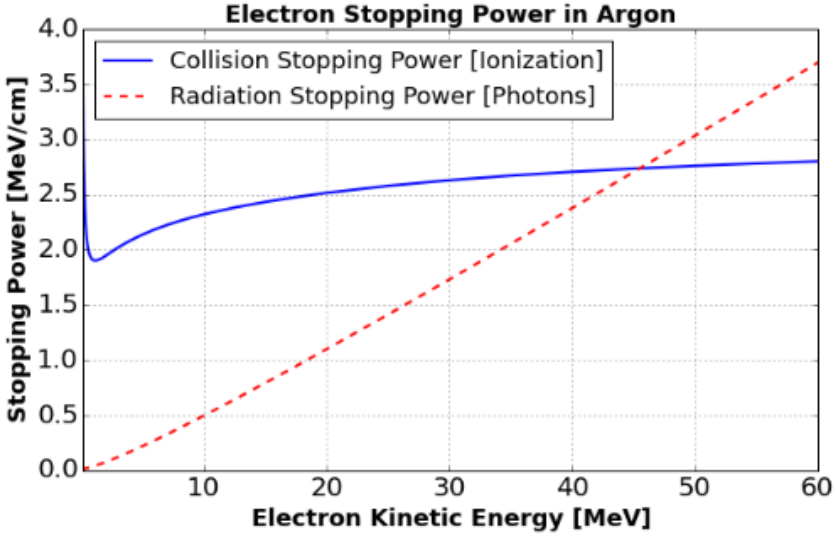


Michel e⁻ Spectrum

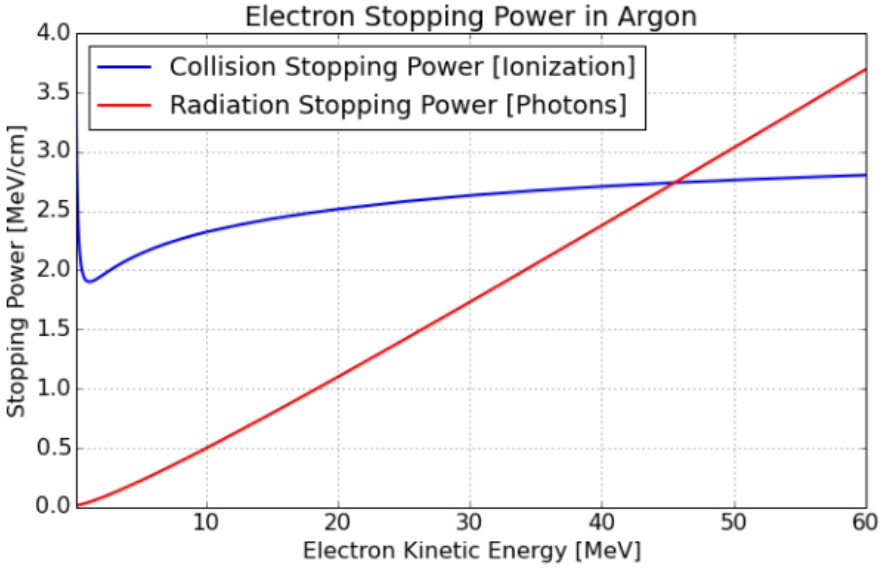


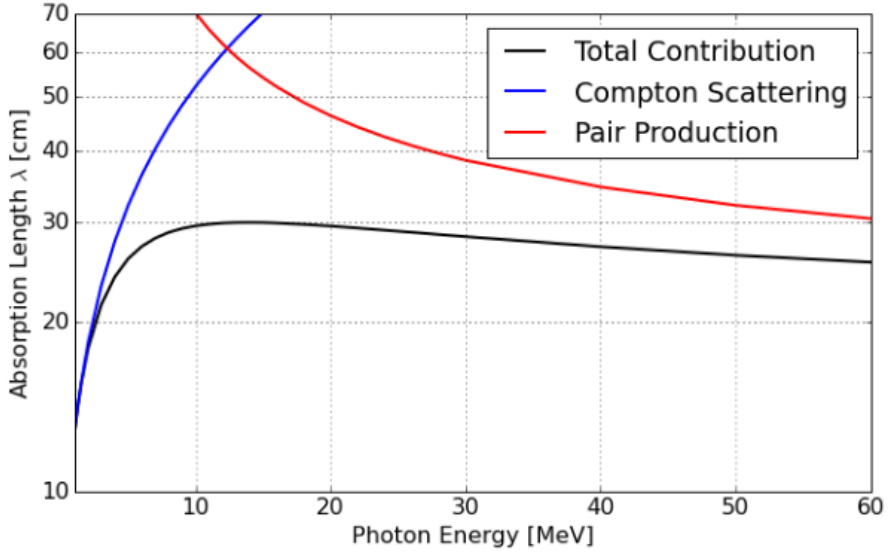


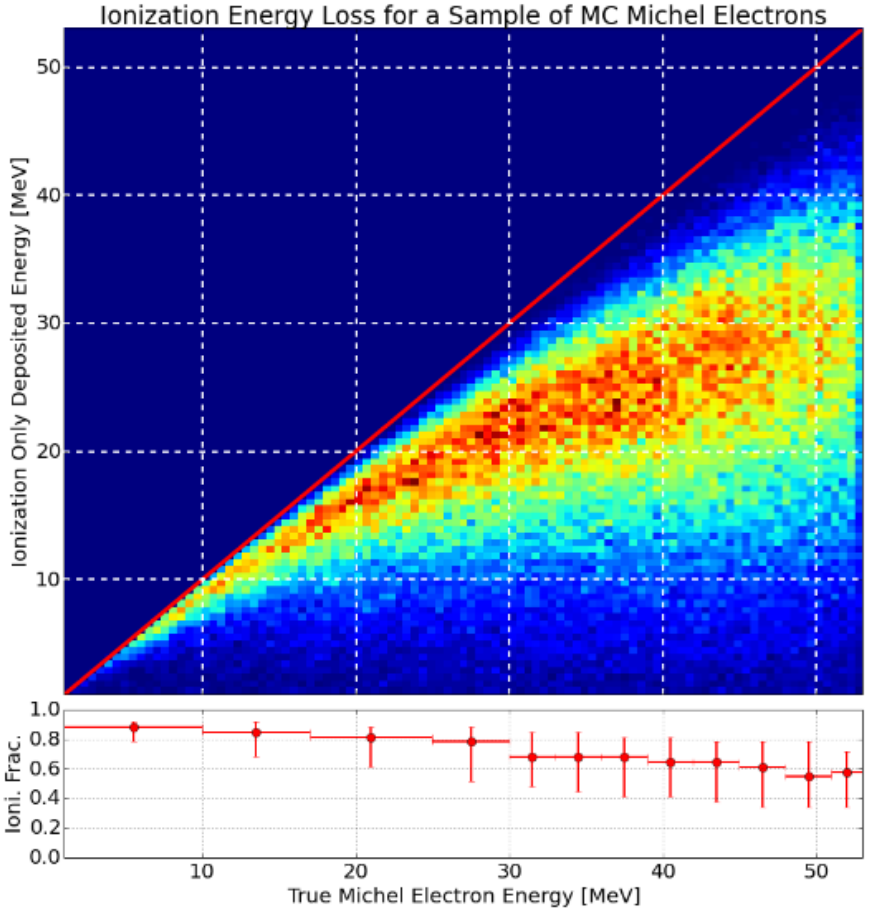


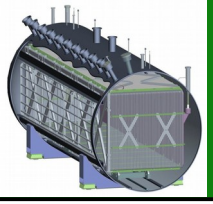


Michel e- Energy Loss







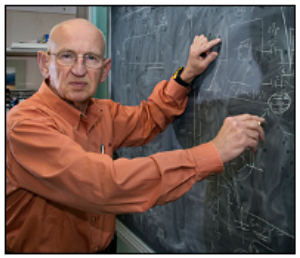


LArTPC: Early History

Early History of the Development of LArTPC

- W. Willis and V. Radeka, Liquid argon ionization chambers as total absorption detector, NIMA 120:221 (1974)
- D. R. Nygren, The Time Projection Chamber: A New 4π Detector for Charged Particles. eConf. C740805:58 (1974)
- H. H. Chen et al. A Neutrino detector sensitive to rare process. I. A study of neutrino electron reactions. FNAL-Proposal-0496 (1976)
- C. Rubbia, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)

William Willis



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